

**Growing southern Appalachian hardwood forests for both timber and carbon storage
value: Is there a trade-off?**

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ABSTRACT

The emerging voluntary forest carbon storage market has important implications for landowners and stakeholders interested in utilizing land for both timber harvest and carbon storage.

Voluntary forest carbon credit agreements are often (deferred or limited harvest) scenarios where payment for carbon storage is accrued over an agreement interval and harvest restrictions are removed after the interval. Over this interval however, the change in value of timber is a concern; forest volatility, complex ecosystem relationships, and economic uncertainty provide the possibility that timber included in a carbon storage agreement might devalue over time from a reduction or preclusion of management intervention.

If the potential devaluing of timber post-harvest is not recuperated by carbon payments over the interval, then the land could be considered more valuable as timber alone with the option to fully harvest. The inverse could be true as well, where post-interval timber value and accrued carbon storage value are more than the timber alone.

This project demonstrates how real forest plot data from the Forest Inventory and Analysis databases; forest modeling capabilities from the United States Forest Service's Forest Vegetation Simulator; and regionally specific forest sorting data could be combined to model dynamic timber and carbon values for common hardwood forests in the southern Appalachian region.

The results of this project showed a potential trade off in timber and carbon storage values, with sensitivities to price per ton CO₂ and discount rate. The simulated forest plots increased in total value over time when Net Present Value was undiscounted. However, against inflation or stock market return rate, the forest plots lost value on average. The price per ton CO₂ showed a sensitivity where higher carbon values created tradeoff periods where the forest plots sometimes gained value.

Additionally, changes in species composition and wood products profile consistent with the known trends of mesophication were observed. This suggested that the simulated carbon agreements were furthering an existing mode of forest degradation.

This project proposes that utilizing land for both timber harvest revenue and carbon storage payments could have negative economic and ecological implications. These implications and recommendations for continued research are discussed.

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Chapter 1: Introduction and General Information

Forest Carbon Credits

In the past, forest carbon credits have mostly been reserved for industrial businesses and governmental organizations looking to offset carbon emissions (Corbera et al., 2009). This system is known as the “compliance carbon market” and is where larger polluters purchase ‘offsetting’ carbon credits based on legislative requirements. In 2021 the compliance carbon market was estimated at being worth \$851 billion dollars with 15,811 metric tons of CO₂ emissions sequestered (Kreye et al., 2023). With such a valuable market and a growing acceptance of the compliance carbon market, the appeal to expand carbon storage opportunities has increased. This increased interest in forest carbon opportunities has sparked the emergence of the “voluntary carbon market.” The voluntary carbon market is where non-industrial forest landowners can choose to delay or reduce harvest with aims to increase forest carbon stocks in the same fashion as the compliance market agreements (Lee et al., 2018). In exchange for reducing or deferring harvest on their land base, these landowners get paid for the resulting increase in carbon stocks on their land. While still behind the compliance market, the voluntary market is gaining popularity with a valuation of \$1.985 billion and 493 metric tons of CO₂ emissions sequestered in 2021 (Kreye et al., 2023).

The compliance and voluntary carbon markets operate similar sequestration requirements, development stages, and verification processes (Kreye et al., 2023). Where the two markets differ is the scale of the carbon storage agreements; the voluntary market operates on a much smaller scale than the compliance market (Kreyes, 2023). In the compliance market, agreements are typically a 100-year initial contract with longer term contracts and extensions being commonly offered (Kreyes, 2023). The minimum acreage of these compliance agreements is variable depending on the developer, but it has been suggested that at least 1,500 plus acres is needed for carbon storage agreements to be profitable. (Parajuli et al., 2019) Due to these large spatiotemporal requirements, the demand of the carbon offset market has traditionally been met by large industrial, forest landowners that are able to diversify management and have more

acreage held in a carbon agreement without depleting land used for timber production or other natural resource management. In the voluntary market these requirements are less limiting. Contract lengths can be from 1-100 years with 40 years being a commonly cited minimum (Kreyes, 2023) (Canham, 2021). The minimum acreage is flexible as well with agreements commonly ranging from 1-40 acres in size. Larger acreage agreements are also common in the voluntary market, but US forest owners only own an average of 67.2 acres of forest land giving preference to these smaller agreement sizes (Parajuli et al., 2019). The translation of large carbon storage agreements at the compliance scale to smaller agreements at the voluntary scale is not yet fully understood.

Given that these smaller voluntary agreements are growing in popularity, it is important to acknowledge the potential effects of reducing or delaying harvest under these carbon storage agreements (Kreye et al., 2023). During the agreement, trees that could have been harvested might die, resulting in a loss in potential timber value. Similarly, non-commercial harvesting through thinning or culling is an important mode of forest management. The possibility of tree mortality and restricted management opportunities could create a change in forest species composition where less valuable trees take over the local ecosystem while restricting the growth of more valuable trees. Both of these effects could come with a potential change in forest products where the resulting post-interval forest is not able to produce equally valuable product outputs as the pre-interval forest. While the carbon payment may help offset the value lost from reduced harvest, the financial implications of potentially degrading effects on timber may also be important (Gorte, 2010). These reductions may be especially important to smaller forest landowners looking to hold a majority or the entirety of their land base in a carbon agreement.

These voluntary market carbon agreements are growing in popularity and quickly spreading across the United States. Though they have been popular in other parts of the US, these agreements are now expanding to the southern US (Galik et al., 2013). Some successful voluntary carbon agreement businesses or organizations currently operating in the southeast include TerraCarbon, The Family Forest Carbon Program, Verra Carbon Registry, and Natural Capital Exchange (Southern Group of State Foresters, 2024). As these agreements become more popular in the region, it is important for landowners to fully understand their implications.

Project Goal and Hypothesis

Given the increasing popularity of the voluntary carbon market and its arrival to the southern United States, this thesis project intended to evaluate the potential economic and ecological implications for a small parcel, southern Appalachian hardwood forest landowner entering a short term, deferred harvest carbon agreement. Based on the complex regional ecosystem and historic forest degradation of the region, it was hypothesized that:

1. Southern Appalachian hardwood forests are predisposed to potentially negative consequences of altered management regimes initiated by carbon storage agreements.
2. Avoiding or reducing harvest to receive carbon credit payments could be counterproductive economically due to the relatively high value of timber and the potential for reductions in timber value over an agreement interval.
3. This counterproductivity will be accompanied by ecological and commercial forest degradation instigated by existing environmental conditions.
4. Tree mortality; changes in species composition; changes in potential products output; and the time value of money over a carbon storage agreement period will be the drivers of this potential reduction in timber value and forest degradation.

To test these hypotheses, a model combining the Forest Inventory and Analysis's (FIA) forest plot data and the Forest Vegetation Simulator's (FVS) forest growth and yield model was used to apply a deferred harvest carbon storage agreement to common forests of the southern Appalachian hardwood region. This model was primarily looking at a tradeoff relationship between timber and carbon values. In this tradeoff, the hypothesized value lost by degrading timber must be recuperated by the value gained by accruing carbon in a carbon storage agreement in order for the agreement to be economically viable. If the potential loss is not recovered by accrued carbon, then the agreement is not economically viable. Additionally, this

model was also designed to look at potential forest degradation happening alongside this timber and carbon tradeoff relationship.

This project looks at the current state of southern Appalachian hardwood forests; the potential for their degradation; the use of publicly available forest plot data; and the application of an industry standard forest modeling program to predict economic and ecological implications of implementing forest carbon agreements in the southern Appalachian hardwood region. Similar analyses looking at carbon and timber have been conducted, but this combination of southern Appalachian hardwood forests, FIA data, and FVS software is novel. The audience for this thesis project is landowners, stakeholders, and policy makers involved with southern Appalachian hardwood forests. The results and trends presented are meant to influence future participation or regulation of carbon storage agreements in the southern Appalachian hardwood region.

Southern Appalachian Hardwood Forests

The arrival of forest carbon agreements in the southeastern United States requires consideration of the ecology of the region. The southern Appalachian hardwood region is complex: the native forests include many species, landforms, and growth conditions. This combination results in highly heterogeneous forests that have many variables that must be considered and dynamics that are difficult to predict (Jenkins et al., 2015). The regional tree species diversity of the southeast is one of the highest in the country. Despite this species diversity and varied environmental conditions, some generalization about southern Appalachian hardwood forests can be made (Perry, 2022).

The common landforms; edaphic soil conditions; slope and aspect relationships; and overall regional climate create overlapping growing conditions that encourage similar modes of regional plant dispersal, establishment, and succession (Perry, 2022). Though each forest parcel growing in a permutation of these environmental conditions is unique, this regional similarity creates conditions where forests of similar composition, appearance, and function appear across the landscape. While these patterns can lend themselves to structured categorization of forests by condition, the combination of any number of these many species or environmental conditions

still preserves unique interspecies behavior and localized growth dynamics. This relationship leads to a dichotomy where forests can be grouped by similar attributes but must be observed as unique entities when considering management or future growth conditions. In terms of applying carbon agreements to this varied (albeit categorizable) landscape, these varied conditions create additional considerations that must be made when compared to the considerations needed for a more homogenous landscape such as coniferous forests or pine plantations (Belote et al., 2011). While one forest stand is not directly comparable to another, one part of the region is comparable to another part of the region. This regional commonality lends itself to categorization but not to predicting forest behavior. In order to observe behavioral trends, some categorization is appropriate, but overall trends should be derived from a collection of sampled forests.

In regard to behavioral trends, a concern with the arrival of voluntary forest carbon agreements to the region is the resulting effects on timber stock of the forested land. The southern Appalachian hardwood region is responsible for much of the hardwood lumber produced in the US (Oswalt & Turner, 2009). The trees that are harvested are relatively high value, an important income source for landowners, and provide economic activity for rural communities within the region. Timber value in southern Appalachian hardwood forests is largely tied to size and species (eg. larger-diameter, moderately shade-tolerant oaks and hickories). With carbon programs expanding into the southern Appalachian hardwood region, the question is how reduced or deferred harvest will affect future tree size, species composition, and potential forest products.

Potential for Degradation

Forest carbon agreements commonly defer or reduce harvest for a time on the reserved lands that they include. This change or reduction in management could have potentially negative consequences to forest growth. During this time, the existing trees may continue to increase in size and timber value, thus increasing the future timber value as well as accruing carbon value. Despite this growth, there is also the potential for timber degradation. Although many of southern Appalachia's trees have multi-hundred-year life spans, the average forest age is typically much lower. Some species of tree in the region can live to be 600 plus years old, but average forest stand age is closer to 100 years old (Anderson et al., 2013). Given that mortality

is not at guaranteed intervals, there is potential for valuable species (which could have been harvested prior to an agreement) to die over the agreement interval and thus not have value at the end of the harvest deferral period.

Another consideration is a change in species composition during the carbon agreement. While this change can be from natural succession alone, much of the hardwood forests in the southern Appalachian hardwood region have undergone additional changes that have altered the progression of natural succession. Most of the region's forests include some remnants of human induced change from historic forest management, fire suppression, agricultural conversion, over harvest, and other anthropogenic influences from the 19th and 20th centuries (Pan et al., 2011). This anthropogenic influence paired with the irreversible change from the continental demise of the American chestnut (*Castanea dentata*) has created regional forest conditions of disrupted succession and unsustainable age structures (Elliot & Swank, 2008). Due to this historic change, many of the valuable species in the region (primarily oaks and hickories) will no longer regenerate in the same, desired proportions without human intervention.

The term typically used to refer to this historic change is “mesophication,” and it refers to a primarily human initiated transition from a diverse set of fire-tolerant and less shade-tolerant species, to a smaller set of fire-intolerant and more shade-tolerant species (Nowacki & Abrams, 2008). In southern Appalachian hardwood forests, the more fire-tolerant and less shade-tolerant species that are being suppressed are the more valuable species (e.g. oaks). Allowing a forest already experiencing these degrading forces to grow without intervention may worsen the problem. The resulting forest could contain a higher proportion of less valuable species. Even if the valuable species persist, the altered forest conditions will have allowed the less desirable species to grow as well and will ultimately detract from the growth and regeneration potential of the more valuable species. Though the forest will continue to grow, the concern is that the resulting stock could be lower in grade and value.

The same relationship is true for products output. A forest with an altered species composition will have an altered products profile. A desirable state in terms of economic value for southern Appalachian hardwood timber is a forest full of mature trees of desirable species that create

many (higher value) hardwood saw logs with less (lower value) pulpwood logs (TimberMart-South, 2023). A degraded products profile could include increased pulp production or the presence of sawlogs of less valuable species. These problems are typically circumvented through silvicultural management where more desirable species are promoted, and less desirable species are removed by harvest or ‘timber stand improvement’. This management is less possible in deferred harvest scenarios, and the resulting products profile may be suboptimal compared to pre-agreement conditions.

The degraded conditions of southern Appalachian hardwood forests have the potential to negatively interact with carbon storage agreements. Altered management regimes and potential harvest reductions pose risks for landowners losing money on existing timber. Likewise, historic change in forest conditions and existing mesophication has created new conditions where carbon storage agreements could encourage further damaging of environmental conditions. Both of these potential interactions could also have effects on the amount and kind of wood products produced in southern Appalachian hardwood forests. Landowners, stakeholders, and policymakers involved with southern Appalachian hardwood forests should be aware of these potential consequences before engaging with carbon storage agreements.

Forest Inventory and Analysis

Forest stand data for this project comes from the USDA Forest Service’s Forest Inventory and Analysis program (FIA). The FIA data collection is a national, on-going forest sampling scheme where individual tree data, site conditions, and other plot ecological data is collected in a grid across the country (Gray et al., 2012). This grid is broken into 6,000-acre hexagons (Shaw, 2008). The data taken in an FIA plot are combined with landform analysis and other natural resource information to make predictions about the total state of forests in the US at this expansive scale (Gray et al., 2012).

FIA data have many advantages that suited the needs of this thesis project (Tinkham et al., 2018). First, FIA data have national coverage, so the entire southern Appalachian hardwood study area could be assessed. Second, the forest sampling data is free and available to the public

through the FIA DataMart for research purposes. A full FIA data plot primarily consists of four 1/24-acre plots known as subplots (Shaw, 2008). These subplots are akin to standard forest sampling plots. Each FIA subplot records the needed data to make both timber and carbon prediction; recorded attributes include individual tree species, tree size, stand age, and carbon content. Third, FIA plots are known for their data collection quality. FIA has strict protocols where every plot is precisely sampled, periodically updated, and tracked through time (Shaw, 2008). This project used FIA subplots as representative forest plots that were then scaled and used to make predictions about one-acre blocks of forest.

Modeling of Forests and Forest Vegetation Simulator

This analysis used FIA data on current forest inventory to predict future forest value. To do the modeling of forest development, the USDA Forest Service's Forest Vegetation Simulator (FVS) was used. FVS is the standard for forest modeling software in the US. The program originated from Albert R. Stage's "Prognosis Model for Stand Development" in Moscow, Idaho (Stage, 1973). Since its inception, the program has been through continued development and many iterations (Dixon, 2002). The result of this development is a region-specific modeling program that "has been calibrated for specific geographic areas (variants) of the United States" (Dixon, 2002). This allows FVS to be widely applicable, but also geographically specific, where a majority of "forest tree species, forest types, and stand conditions" can be simulated with appropriate and relevant pre-existing metrics (Dixon, 2002).

The program is an individual-tree, distance-independent growth and yield model that functions on a tree diameter basis and uses a competitive growth calculation known as the "crown competition factor" (Dixon, 2002). These attributes allow for simulations that can be used to make predictions "about how forest vegetation will change in response to natural succession, disturbances, and proposed management actions. The software is a system of highly integrated analytical tools that is based upon a body of scientific knowledge developed from decades of natural resources research and experience. Thus, FVS is frequently trusted for forest research and management purposes.

Chapter 2: Literature Review

A literature review was conducted focusing on the four major points of this project:

- 1) Voluntary forest carbon agreements in relation to forest management.
- 2) Trends in southern Appalachian hardwood forest degradation and the potential consequences for forest landowners.
- 3) The use of FIA and FVS as research tools, and examples of how these resources have been used for timber and carbon research simultaneously.
- 4) Examples of USDA and USFS publications that relate to the decisions made for building the forest modeling scheme used in this project.

Voluntary forest carbon agreements

Potential of Carbon Storage Agreements

The voluntary forest carbon agreement market has created an opportunity for landowners to defer harvest on their land and gain value from the carbon storage that occurs during this deferment; currently, this market is in a mode of optimism but uncertainty. Forest carbon storage agreements can be an attractive option for landowners looking to contribute to climate change mitigation or gain additional revenue from their forest land. This option is particularly appealing to landowners who are not interested in timber harvesting and perceive no penalty from harvest restrictions. However, for landowners that are interested in timber harvest revenue as well as carbon storage payments, a carbon credit agreement could potentially have hidden, negative consequences. This possibility represents a gap in the knowledge of carbon storage agreements; the process of carbon sequestration and storage is known, but the knowledge on responsible implementation of this process is limited. Work by Merger and Pistorius (2011) suggested that the voluntary forest carbon market suffers from a lack of “efficiency and legitimacy.” Despite a

rise in popularity and the formal establishment of voluntary carbon storage businesses, these agreements currently lack a standardization of agreed effectiveness (Merger & Pistorius, 2011). Similar opinions were presented in work by van der Gaast et al. (2018) where the authors described the contributions of forest carbon agreements to combating climate change. The authors noted that forest carbon sequestration could play a significant role in the reduction of GHG emissions but have not yet fulfilled their potential to do so. They cited this unfulfilled potential as the fault of a “mismatch between theoretical potential and practical implementation,” where forests are known to be excellent at sequestering and sinking carbon but have too many uncertainties to be broadly applied (van der Gaast et al., 2018).

Regionality of Carbon Storage Agreements

One source of this uncertainty was described as differing forest behaviors due to regionality; the sequestering and storage potential of a forest depends on the limitations and influences of the local environmental conditions (Belote et al., 2011). This differing regional behavior starts at the global scale and filters down to the single forest scale. At the top end of this scale, work by Liu et al. (2012) detailed a basis for how this sequestration potential varies globally through the different biomes. Additional work by Raihan et al. (2019) explored this same sequestration potential through a ranking of the continents. Moving down the scale, more specific regional work was explored by Cademus et al. (2014) in the article ‘Analyzing Trade-Offs, Synergies, and Drivers among Timber Production, Carbon Sequestration, and Water Yield in *Pinus elliotii* Forests in Southeastern USA” where the authors discussed management strategies for their pine plantations in their region but insisted that their findings were not applicable for other portions of the US. In the article “From sink to source: Regional variation in U.S. Forest carbon futures,” Wear et al. (2015) found similar results where regionality affected carbon sequestration potential across the US. Furthermore, Woodbridge et al. (2022) explained how sequestration potential is equally affected by localized ecological conditions in addition to regional variation. Carbon sequestration efforts must be viewed through a specific, regional lens to reduce uncertainty and increase effectiveness.

“Co-benefits” of Carbon Storage Agreements

Another uncertainty is the exploration of “co-benefits” in carbon sequestration agreements (Lee et al., 2018). As detailed by Lee et al. (2018), “co-benefits” in carbon agreements are the other forest ecosystem services that could be affected by the addition of carbon management. Such systems mentioned were timber, wood products, ecosystem services, socio-economic influences, and ethical environmentalism (Lee et al., 2018). The authors claimed that these related systems must be included as part of carbon sequestration research and projects; the inclusion of these systems increases the participation in, and the validity of, carbon storage transactions.

Studies similar to this thesis project addressed both the regionality and “co-benefit” criteria of carbon storage agreements (Lee et al., 2018). Work by Roise et al. (2016) analyzed Net Present Value optimization when managing for both timber and carbon sequestration in North Carolina and found that less intense management would encourage participation in carbon agreements while also increasing the accumulation of carbon sequestered. Schwenk et al. (2012) explored similar “co-benefits” using “multi-criteria decision analysis” to explore management options for forests in Vermont (Lee et al., 2018). This project considered carbon, timber, and biodiversity as “co-benefit” metrics; the authors found that strong consideration for one metric had influencing effects on other metrics (Lee et al., 2018). An article by Carpentier et al. (2017) used a similar analysis to simulate the behavior of New York forest woodlots for the use of timber, carbon, and habitat quality. The authors found that the desires of stakeholders influenced the proportion of consideration given to any one ecosystem service. These studies all explored “co-benefits” of carbon sequestration management (Lee et al., 2018). Though the word ‘benefit’ typically holds a positive connotation, these “co-benefits” also included the possibility of negative consequences where a tradeoff was examined when multiple management objectives were considered (Lee et al., 2018). Managing for only one objective was often to the detriment of another objective and the point of their exploration was the potential for addressing multiple objectives rather than the maximization of one objective. This thesis project explored the potential tradeoff of multiple objectives for the same forest plots. Much like this thesis project, these studies used either FIA, FVS, or both to explore the potential of multiple forest management objectives; however, this

thesis project is novel in its application of these tools to analyze the southern Appalachian hardwood forest region.

Willingness to Participate in Carbon Storage Agreements

Due to uncertainty and lack of awareness, varying degrees of willingness to participate in forest carbon agreements has been found during previous research. A meta-analysis of United States landowner's participation willingness by Sharma and Kreye (2022) found that landowner objectives; outreach and education; contract details on duration and size; and expected monetary return were all driving factors in willingness to participate in carbon storage programs. They specifically found that landowners with timber objectives were more wary of participation than landowners with preservation or other non-harvest objectives. Similar results were found by Khanal et al. (2017) when researching willingness to participate for landowners in the Southern United States. Despite wariness and varied willingness to participate, estimates of participation did still occur meaning that additional research is warranted for the effects of multi-objective forest management. This thesis project explored "co-benefits" in the southern Appalachian hardwood region that might influence landowner willingness to participate in carbon sequestration agreements (Lee et al., 2018).

Carbon Storage Agreements in This Thesis Project

The full suite of effects from entering into a reduced or deferred harvest carbon credit agreement are not yet known; these effects need to be explored further for the benefit of landowners and stakeholders. These landowners and stakeholders should be aware of the potential economic and environmental interactions these forest carbon credit agreements pose. Likewise, policy should be made with respect to a deeper, scientific understanding of the effects these carbon credit agreements might have. A better understanding of the potential drawbacks might reframe participation in and policy on forest carbon credit agreements. The current literature regards forest carbon storage agreements as overall unstudied. A big area left in this knowledge gap is the regional effects and applications of forest carbon storage agreements; regionality greatly determines the success and consequences of forest carbon storage agreements. Likewise, further research must be more comprehensive and include consideration for all effects, or "co-benefits,"

that could come with forest carbon storage agreements. Despite these gaps, there is still willingness to participate in forest carbon storage agreements.

This thesis project covers a specific region (southern Appalachian hardwood forests) and potential “co-benefits” (timber value, species composition, and products output) of carbon storage agreements in that region. These analyses have not yet been made for this region and the results of this thesis project could be used to influence future participation in forest carbon storage agreements in the region.

Trends in Appalachian Forest Degradation

Defining a Study Area

The objective of this study was to observe trends in southern Appalachian hardwood forests. Appalachia is frequently defined by concurrence of adjacency to the Appalachian Mountains and their associated ecosystems. However, a strictly geographical definition does not properly bound Appalachia either; as can be seen on the Forest Inventory and Analysis’s “National Forest Types Group Map” (FIA, 2024). This map is included in the Appendix of this thesis project.

A change in both forest coverage as well as forest type is observed when moving too far in any cardinal direction from the center of the Appalachian Mountain range, which loosely aligns with central Virginia and the eastern border of Tennessee. The characteristic oak, pine, and hickory forests transition to more coniferous and northern hardwood forests (to the north), or drier, pine-dominated piedmont forests (to the east). While still technically part of the Appalachian Mountains, many peripheral areas and the northernmost regions are characteristically different ecosystems than the southern Appalachian hardwood forests that were the focus of this thesis project.

A project from the Geography Department at Virginia Tech titled “Mapping Appalachia’s Boundaries: Historiographic Overview and Digital Collection.” bridged the cultural and ecological definitions of southern Appalachia (Scales et al., 2018). This project was a

compilation and comparison of many different, primarily historic, scholarly, and political, definitions of Appalachia. The most relevant definition of Appalachia from this study is an excerpt from John Alexander Williams's book "Appalachia: A History." (Williams, 2002) In his book, Williams compared six historic definitions of Appalachia and observed where they overlapped. The areas that overlapped from all six definitions are what Williams referred to as "core" Appalachia (Williams, 2002). This definition was closely aligned with the "National Forest Types Group Map" for the chosen forest composition and included geographic referencing for use in the modeling methodology.

Mesophication of the Southern Appalachian Hardwood Region

The current state of southern Appalachian hardwood forests within the geographic study area is the result of historical fire suppression, land use change, timber harvest, and other human intervention (Pan et al., 2011). These effects have resulted in the advent of 'mesophication': a transition from more open canopy, fire-adapted, oak-dominated landscapes to fire-intolerant closed canopies (Nowacki & Abrams, 2008). This transition is associated with a reduction in species diversity, and the dominance of shade-tolerant species (Vander Yacht et al., 2018). Mesophication ultimately results in oak and hickory mortality (Radcliffe et al., 2021). The mortality of these species could be problematic as the oak and hickory genera are connected with the important and valuable timber outputs for the Appalachian region (Oswalt & Turner, 2009). This relationship of transition in species composition, and the ultimate mortality of desirable species, was how this thesis project defines 'forest degradation'; when mesophication trends push forests into less desirable timber profiles.

Management can avoid mesophication through prescribed fire and other silvicultural treatments (Hutchison et al., 2024). Without such interventions, mesophication will continue to a state of 'degradation', as defined above. Given that the assumed voluntary carbon agreements are no-intervention and no-harvest growth scenarios, it was anticipated in this project that mesophication would progress along with the timber and carbon tradeoff relationship.

Appalachian Forest Degradation in This Thesis Project

The literature and existing knowledge base of this issue suggested that entering into carbon agreements could eventually encourage further forest degradation. For owners looking to engage in multi-use management, carbon agreements, discouraging active management could result in degraded forest conditions. Current literature has not yet connected forest carbon storage agreements to the progression of existing mesophication. This thesis project addresses how deferred or limited harvest could encourage mesophication in southern Appalachian hardwood forests as well as the potential economic and ecological consequences of this encouragement.

The use of FIA and FVS as research tools

The Forest Inventory and Analysis data collection program as well as the Forest Vegetation simulator have frequently been used as tools in forest modeling and growth prediction research. The data collection process of the FIA included all the information needed to make the predictions this project sought to make (Gray et al., 2012). Likewise, the FVS software was designed to accomplish the modeling tasks needed by this project, which were growth and yield monitoring for both timber and carbon over many years (Crookston & Dixon, 2005). These studies cited represent where FIA, FVS, or both have been used to assess similar questions to carbon and timber tradeoff.

Use of FIA Data in Forest Modeling

Wurtzebach et al. (2019) supported the use of FIA data for federal forest planning under the National Forest Management Act of 2012. The researchers suggested and gave references to the qualifications of FIA data that matched the demands of the NFMA. The article identified FIA data as a “strong and defensible science base for forest planning and adaptive ecosystem management in an era of rapid change” (Wurtzebach et al., 2019). Additionally, the article included different planning applications covered under the NFMA such as “carbon stocks,” “timber production,” and “species composition” (Wurtzebach et al., 2019). All of these applications were direct components of this thesis project, where FIA data was used to make predictions for all three.

In a companion article published in the same journal, Hoover et al. (2020) expanded on the idea of using FIA data as input for forest planning. The article first introduced the advantages of raw FIA data and then identified many additional USDA and USFS databases or tools that are compatible with FIA data. Hoover et al. (2020) suggested that these compatibilities greatly expand the usefulness of FIA data and allow for a wide arrange of analyses outside of what base FIA data shows. Though not listed in their article, the FVS software used in this thesis project would constitute as an expanded compatibility as detailed by Hoover et al. 's (2020) article. National Forest planning, such as that being done in the Northern Forest Region as described by these articles, involved the use of FIA data in a manner similar to that used in this thesis project, a regional analysis rather than parcel specific.

Combining FIA and FVS

An example of combining FIA and FVS came from Moeller et al. (2024) in “Profitability analysis of southern plantations through timber alone or timber and carbon integration in pine-sweetgum mixes”. This article used FIA data in FVS simulations to model the Land Expectation Value (LEV) of different Loblolly and hardwood species mixtures at varying planting densities and species compositions. The study suggested “that mixed forest plantations offer an economically attractive option for forest landowners and provide a viable alternative for diversifying traditional forest management in the region” (Moeller et al., 2024). Much like this thesis project, this article used both timber and carbon as components of value (Moeller et al., 2024). Other similarities included ignoring the possibility of natural disturbance; acknowledgement of carbon and discount sensitivities; focusing on the southeastern United States; and using timber value data from TimberMart-South (Moeller et al., 2024).

Smidt et al. (2012) used FIA data and FVS modeling to quantify the amount and economic feasibility of logging residuals. Much like this thesis project, their study used separate valuing of pulpwood, saw logs, and residuals The researchers also used TimberMart-South as a pricing source (Smidt et al., 2012). One major inclusion of their work similar to this thesis project was the use of the “Forest Type” attribute to sort FIA plots for suitability of use. “Forest Types” were polled to select plots that most representatively accounted for their study area (Smidt et al., 2012). Similar sorting of “Forest Types” was found in the work by Raymond et al. (2015) where

the researchers combined FIA data with FVS modeling to examine “post-disturbance forest carbon accumulation.”. Their study used the FIA and FVS combination to see how carbon stores recovered after different intensities of fire, harvest, and insect disturbance. Similar work was shown by Zhao et al. (2024) where the FIA and FVS combination was used in conjunction with Life Cycle Assessment methodology to compare carbon stock accumulation between uneven-age and even-aged forest management. This comparison was related to greenhouse gas (GHG) emissions to further extrapolate trends into the greater climate change discussion sphere (Zhao et al., 2024).

Diaz et al. (2018) presented similar work in the study “Tradeoffs in Timber, Carbon, and Cash Flow under Alternative Management Systems for Douglas-Fir in the Pacific Northwest.” This study included different management regimes to determine their impact on carbon and timber value tradeoffs (Diaz et al., 2018). An assessment of maximizing Net Present Value or NPV, as well sustained timber yield, were two of the priorities named in their study (Diaz et al., 2018). Similar priorities were conducted in this thesis project where change in NPV was tracked over time as well as species composition and products output. The species composition and product output were part of sustained timber yield.

The combination of FIA data and the FVS software has been used numerous times for research purposes. This combination is defensible, adaptable, and used frequently. Based on the scope of this previous research base, the combination was deemed appropriate for use in this thesis project.

Use of FIA and FVS with Other Resources

In addition to the FIA and FVS combination, much of the aforementioned research included contributions from additional programs, resources, and tools for the post processing of simulated data. While FIA data, FVS modeling, and their combined forces are robust tools alone, the application of their capabilities are usually aided by additional programs and resources. The additions made to these tools are what allows for regional focus and data analysis in projects using FIA data, FVS modeling, or both tools simultaneously. This thesis project heavily relied on post processing work through R. R is a common and widely used statistical coding tool used

across many disciplines including forest research applications. Stanke et al.'s (2020) work in the study “rFIA: An R package for estimation of forest attributes with the US Forest Inventory and Analysis database” described a publicly available R code package that interacts with FIA data. This program is able to read the complicated and non-user-friendly SQL language of the FIA databases and allows users to track spatial-temporal forest attributes without manual manipulation of the FIA data (Stanke et al., 2020). The authors provided a working example of their R package with a case study tracking the “decline of ash (*Fraxinus spp.*) populations across the Lower Peninsula of Michigan following the establishment of emerald ash borer (*Agrilus planipennis Fairmaire*)” (Stanke et al., 2020). They explained how this open access package could increase the public usability of a powerful forest data set. Similar work was conducted by Atkins et al. (2022) in the study “Open-Source tools in R for forestry and forest ecology.” The authors in this article reviewed and compiled 83 open-source R packages that pertain to forest research. The article noted that many forest research programs are proprietary or hidden behind a paywall (Atkins, 2022). They concluded that more open access programs would advance forest research (Atkins, 2022) (Stanke et al., 2020). The package created for this thesis project would be considered one such advancement in this field where an R package that communicates with FVS simulation outputs and is derived from FIA data has been created for forest timber and carbon analyses.

FIA and FVS in This Thesis Project

The studies discussed here were related to timber and carbon dynamics as well as the use of FIA data and the FVS modeling program to explore these dynamics. The literature supports FIA data and FVS modeling as reliable tools for regional forest research. Using these tools, some research has been focused on the Southeastern region, but mainly in pine plantation settings with monoculture or mixed dominant species compositions. While this thesis project also looks at the southeastern region, it has a focus on the species rich and complex forests of southern Appalachia hardwoods. Similarly, previous work has been done regarding active management regimes and their effect on timber and carbon dynamics. This thesis project focused on base growth conditions to make comments on non-intervention (precluded or reduced management) scenarios akin to the current voluntary carbon storage agreements. Much of the previous work explored timber and carbon dynamics of large landholdings, in other regions, and with active

management practices. This thesis project was focused on economic and environmental effects as an expansion of exploring timber and carbon dynamics. Likewise, this project is an expanded research use of existing, public resources and has created a new R package for further, public based research. The review of FIA and FVS as tools was used to draw from the successes of previous research and examine where gaps in current knowledge existed. This thesis project fills the niche for a region, conditions, growth regime, and primary objectives not addressed by contemporary research while also creating an additional tool that could aid with similar research endeavors in a field that lacks this kind of resource pipeline.

USDA and USFS Publications

The combined use of FIA data and FVS simulations for predictive forest modeling is not a novel process. However, both of these resources are robust tools, and the different iterations of their combined use are unique to the application for which they were used. This means that although one analysis might share commonality with another analysis, the specific combination and interpretation of these resources varied based on the researcher's defined purpose.

This thesis project was a hybrid application of these resources much like the other research-based examples. To ensure that the specific combination and adaptations of the FIA data and FVS modeling used for this thesis project was logical, various United States Department of Agriculture and United States Forest Service documents were reviewed for simulation instruction and validation.

Getting Started in FVS

The first group of documents reviewed were the conversion manuals detailing the translation of FIA data to the FVS software. The "Quick-Start Guide to Forest Inventory and Analysis Data in the Forest Vegetation Simulator" was the best source for initial validation information. The Quick Start Guide supported the overall use of FIA data and FVS modeling to observe trends in southern Appalachian hardwood forests (Shaw, 2020). This was the ground level for ensuring that the determined research questions could potentially be answered through this methodology.

The next step was determining what data was best for the purposes of this thesis project. Two journal articles, “Using FIA Data in the Forest Vegetation Simulator” and “A New Conversion of Forest Inventory and Analysis Data for Use in the Forest Vegetation Simulator,” were referenced to create the data structure and sorting from FIA to be usable in FVS for the application of this project (Shaw, 2008) (Shaw & Gagnon, 2019). The first article stated that “FIA subplots may be treated as FVS plots, and the FIA plot is considered a “stand” (Shaw, 2008). This provided a justification to use subplots as the basis of this project when the full FIA plot is also a common basis for analysis. The first article was permission to use the subplot basis, but the final decision to not use full FIA plots as the basis of this project was based on information provided in the second article (Shaw & Gagnon, 2019). The article detailed how “FIA delineates forested conditions based on six criteria: reserved status (available for or prohibited from harvest), owner group, forest type, stand size class, regeneration status (natural versus artificial), and tree density” (Shaw & Gagnon, 2019). This meant that subplots within the same plot could have different conditions and that “selection of condition, whole plot, or subplot as the projection unit can influence how trees are grown by FVS” (Shaw & Gagnon, 2019). Shaw (2008) stated that “this (a decision to use the full FIA plot as the basis) obviously represents a loss of available data, this approach may be acceptable if the projection results desired by users are not particularly sensitive to this compromise” (Shaw, 2008). However, this project was sensitive to this compromise because Forest Type was an integral attribute of the data sorting process. Thus, the plot level was chosen for this project as “preserving the information from intra-plot (subplot) variability may be desirable to some users” (Shaw, 2008).

Project Needs for Viable Modeling

Using this validation, the next document referenced was “Research Applications of the Forest Vegetation Simulator: Documentation and Citation” (Paul Anderson, 2020). This document provided the outline for addressing a research question using the FVS software. The document listed four major areas to consider when creating an FVS research question: 1. Variant Selection, 2. Input Data, 3. Simulation Control, and 4. Output Summarization (Paul Anderson, 2020). The bullet points detailed under these four major distinctions were noted as areas of research for building an FVS model. The bullet points for the sections were worked through in order and three additional documents were used to address these points: “Essential FVS: A User’s Guide to

the Forest Vegetation Simulator” (Dixon, 2002); “Keyword Reference Guide for the Forest Vegetation Simulator” (Dixon, 2002); and “Users Guide to the Database Extension of the Forest Vegetation Simulator Version 3.0 (FVS with SQLite) (Van Dyck, 2000).” All relevant portions identified from “Research Applications of the Forest Vegetation Simulator: Documentation and Citation” were retained for the study based on the research provided by these manuals.

The largest portion detailed for creating a research question was “Simulation Control” (Van Dyck, 2000). Much of this section was not applicable to this study. Many adjustments or calibrations detailed in this section could have been made, but most were left to the default FVS settings due to the large number of plots sampled and the large geographic region covered. This lack of calibration was supported by the findings of the article “Calibrating FVS for the Chattahoochee Oconee National Forest Planning Effort.” (Keyser, 2002). This article noted that “little difference was seen when self-calibration was employed,” as compared to manual calibration for the sampled area (Keyser, 2002). The same article also noted that “even though the relative growth differences are small, adjusting and calibrating FVS is still warranted” (Chad Keyser, 2002). However, this second assertion was dependent on developing calibration statistics for one defined geographic or predetermined management area where the calibrations could be retained and refined for successive research or management endeavors. This thesis project was not bound by a single management area and was instead a generalization of southern Appalachia forests. The level of calibration detailed in the “Simulation Control” section and explored by the “Chattahoochee Oconee National Forest” article would not have translated to the geographic expanse of this thesis project (Van Dyck, 2000) (Keyser, 2002). Thus, the default FVS growth settings were retained for most of this project.

Additional Publications

The other technical manuals referenced were used to determine the details of post processing with additional data. The “Southern (SN) Variant Overview of the Forest Vegetation Simulator” and the “Northeast (NE) Variant Overview of the Forest Vegetation Simulator” were used to reference diameter limits for product classifications and guidance for species sorting (FVS Staff, 2008). The definitions for region specific volume calculations were also pulled from these manuals (FVS Staff, 2008). For carbon prices, “Forest Carbon Estimation Using the Forest

Vegetation Simulator: Seven Things You Need to Know” was used to verify carbon pool units in FVS (Hoover & Rebaun, 2011). By default, FVS runs all “output(s)... in mass of carbon regardless of the unit selected,” which means that “users who require(d) output in terms of carbon dioxide (would) need to convert to carbon dioxide equivalent” (Hoover & Rebaun, 2011)). This project was focused on carbon sequestration and all sequestration values were referenced in terms of carbon dioxide equivalent; thus, conversion was needed later in the methodology. The last manual referenced was the “Users Guide to the Database Extension of the Forest Vegetation Simulator Version 3.0 (FVS with SQLite)” (Crookston, 2003). This manual was a companion to the “Essential FVS,” and used as a vocabulary lookup similar to the “Keyword Reference Guide.” (Dixon, 2002) (Van Dyck, 2000). The “Users Guide to the Database Extension” contained the definitions of all the words and translated them between FIA to FVS definition, base FVS definitions, and FVS database definitions (Crookston, 2003). While similar, many of these definitions change in application between these three distinctions and this reference provided translation between them.

Official Literature in This Thesis Project

The review of USDA and USFS literature supported the construction of the model used in this project. Based on this literature review, the unique combination and adaptations of FIA data to FVS modeling used in this project, supports a subplot-based analysis; with largely default calibration statistics; compatibility with the Southern and Northeastern FVS variants; that comments on both timber and carbon dynamics; and fulfills all the needed criteria to be a proper FVS modeling research endeavor as defined by the USFS. Many of the metrics used have precedent in other studies, official literature, and literature reviews. However, the exact combinations of the metrics used was unique to this project and required a compatibility check. This unique combination was tailored to the focus of this thesis project. However, the specificities of the validated methodology could be adjusted for expanded use in other regions or applications. This creates a basis for other literature to explore the implications of similar timber and carbon dynamics of forest carbon agreements elsewhere.

Chapter 3: Methods

The methodology for this thesis project follows the logical progression of the workflow used to build the forest modeling protocol. The built model works through the following progression:

1. Sort regional FIA forest data to focus on desired southern Appalachian hardwood forests
2. Input sorted FIA data into FVS modeling software and simulate the plots under parameters of a deferred harvest, carbon storage agreement
3. Take FVS modeling results and apply regional species sorting and timber values
4. Apply discount rate and carbon price sensitivities to regionally adapted modeling results to observe changes in value and carbon timber tradeoff dynamics
5. Relate the change of timber and carbon stocks to potential change in ecological behavior independent of economic behavior
6. Synthesize timber, carbon, and ecological tradeoff dynamics from simulation results

Sorting the FIA data narrowed the full suite of available data to the target southern Appalachian hardwood forests study area. Simulating the data in FVS gave change over time growth predictions for timber and carbon under theoretical deferred harvest carbon storage agreements. Applying regional data to the simulation results converted raw growth predictions into economic value predictions. Using discount rate and carbon price sensitivities converted economic predictions into potential real-world scenarios where differing values could change the viability of carbon storage agreements. Relating carbon and timber stocks to ecological change evaluated how carbon storage agreements might also affect forest composition rather than just economics. All of these steps were the basis for answering how carbon and timber values might show a tradeoff relationship under deferred harvest carbon storage agreements as well as how these agreements might contribute to forest degradation in southern Appalachian hardwood forests.

Forest Plot Data Sorting

FIA Plot Design and Plot Data Specification

To begin sorting data, SQL databases for each identified state were downloaded from the FIA DataMart. All following steps of the data sorting process were done at the state level where six state level datasets were identically sorted into six data populations and then were reduced even further into six samples of the sorted data populations.

For the purpose of this project, it is important to understand the difference between FIA plot, subplot, and tree level classifications.

The FIA plot level classification is information that pertains to an entire FIA plot sampling and includes spatiotemporal information and other non-tree ecological sampling data. An entire FIA plot is 1/6-acre in area and encompasses four FIA subplots (*Figure 1*). In the SQL databases, this classification is referenced by the “stand_ID” attribute (Dixon, 2002). This classification was not suitable as data for this project but is conceptually important for understanding the FIA subplot classification.

The FIA subplot classification is information that pertains to one out of four total subplots within a full FIA plot. For this thesis project, the pertinent data at this classification is information about the size, species, and arrangement of trees within the subplot as well as localized ecological data also used for forest modeling. A single FIA subplot is 1/24-acre in area (*Figure 1*). In the SQL databases, this classification is referenced by the “plot_ID” attribute (Dixon, 2002). As introduced in the literature review, subplot level data were used in this thesis project because differing conditions between individual subplots within a whole FIA plot level introduces less filtering specificity for observing trends about specific archetype forests.

The FIA tree level classification is information about individual trees within the subplot classification such as height, DBH, and species (Dixon, 2002). Tree level data is absolute and is not sorted individually; change over time is observed at the subplot level rather than at the single

tree level. For this thesis project, the subplot classification was the sampling unit used in FVS for simulation purposes. The tree level classification is what the FVS software applies growth modeling to for simulating future forest conditions, but these conditions are tracked as an entire unit (subplot classification).

The SQL databases hold individual subplot level classification entries in tables listed as “FVS_PlotInitPlot.” These entries are already compatible for later use with the FVS software (Shaw, 2008). Individual subplots were the classification level used as data in this thesis project and their individual “plot_ID’s” are what was sorted to create a sampling population.

Mapping Boundaries

To define the study area, the “core Appalachia” definition from John Alexander Williams found in “Mapping Appalachia’s Boundaries: Historiographic Overview and Digital Collection.” project was used (*Figure 2*) (Williams, 2002). This map generally followed the boundaries of what would be considered southern Appalachian hardwood forests and included geo-referenced information that was later used for sorting the FIA data. A total of 174 counties from six states (Georgia, Kentucky, North Carolina, Tennessee, Virginia, and West Virginia) were included in the “core” Appalachia definition and used to determine what areas FIA data should come from (Scales et al., 2018).

Using the counties identified by the “Mapping Appalachia” study, only plots that existed in the appropriate counties were extracted from the “FVS_PlotInitPlot” tables (Scales et al., 2018) software (Shaw, 2008). This first level of refinement created a new table of subplots that only occurred in the county-specific target area.

Sorting of Subplots by Age Class

The next level of refinement for this project was Age Class. The attribute “age” is included for each FIA subplot and is an approximate stand age based on representative tree core tests and associated aging factors (Shaw, 2020). This approximate stand age was used to sort forest plots based on the hypothesized forest degradation. The following Ages Classes were chosen because

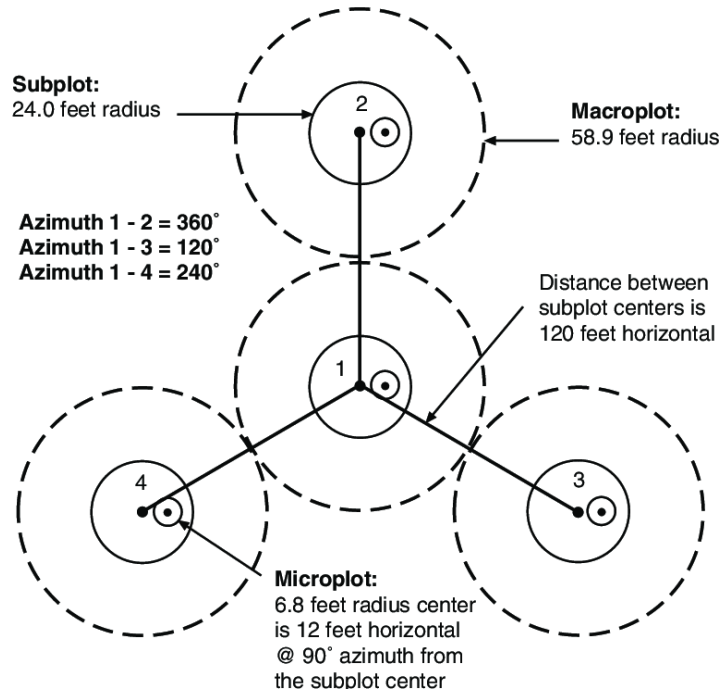


Figure 1: FIA Full Plot Design Layout (Plot vs. Subplot Delineation) (Bechtold & Scott, 2005)

MAP / THREE VERSIONS OF APPALACHIA

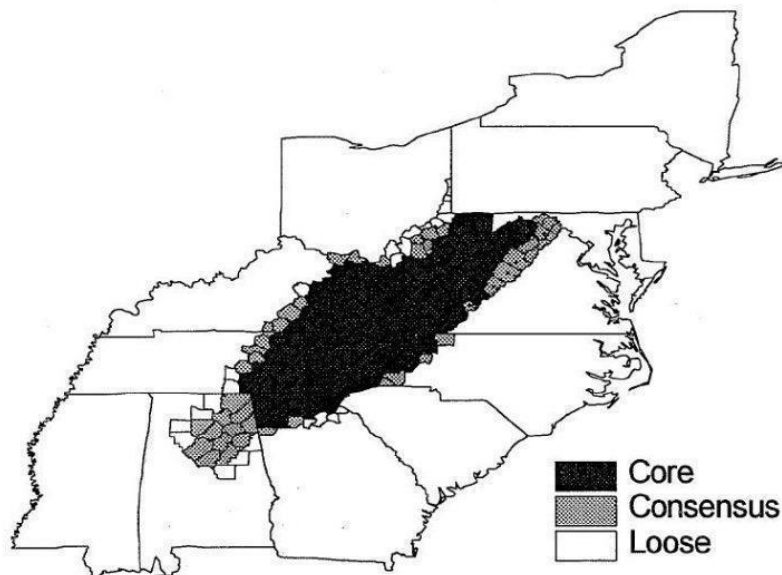


Figure 2: Core Appalachia Map from Virginia Tech's Mapping Appalachia - A Digital Collection (Scales et al., 2018)

they could demonstrate the desired growth dynamics at different stages: 60-80 years old, 81-100 years old, and 101-120 years old.

In terms of average forest age for the region, plots at 60-80 years old represents approaching mature forest that would grow into mature forests over the agreement interval; plots at 81-100 years old represent mature forest that would grow into over-mature forests over the agreement interval; and plots at 101-120 years old represent over-mature forests that would grow into well over-mature forests over the agreement interval (Anderson et al., 2013).

Older Age Classes were excluded from this thesis project because there were too few plots to create a meaningful analysis; the landscape is primarily covered in the determined Age Classes. Younger Age Classes were excluded from this thesis project because they are still growing and less likely to experience the negative effects of maturation during a deferred harvest carbon storage agreement. The focus of this thesis project was the effects of forest carbon credit agreements on the approaching mature, mature, and over-mature hardwood forests that are most prevalent in the region. Based on these characteristics, the previously sorted county table was further filtered into three separate tables (60-80 years old, 81-100 years old, and 101-120 years old) where only plots whose approximate stand age fit into these Age Class divisions (*Table 1*).

Sorting of Subplots by Forest Type

The next step in filtering the data was sorting these age-based plots by Forest Type. This FIA-derived attribute is typically a three-digit code that defines plots by the dominant species and associated structure within a subplot. Unlike Age Class, which was defined by this thesis project, forest type was a filtering characteristic predefined in the FIA dataset. Many Forest Types existed throughout the study area but to be most broadly representative, only the most commonly occurring “Forest Types” were used.

The three unique Forest Types that had the highest counts in each Age Class were selected (*Table 1*). This process was done for all three age class brackets in all six states. For age class 60-80, forest types 502, 503, and 506 were most common. For Age Class 81-100, forest types

Table 1: Total Number of FIA Forest Plots Matching Forest Type and Age Class Sorting Combinations by State

Age Class: 60-80			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	320	680	260
GA	240	432	100
NC	152	196	244
VA	308	280	236
WV	140	532	152
KY	108	944	160
total	1268	3064	1152
Age Class: 81-100			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	152	500	128
GA	200	184	180
NC	308	212	256
VA	504	504	248
WV	200	440	100
KY	12	180	32
total	1376	2020	944
Age Class: 101-120			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	48	108	32
GA	48	68	36
NC	44	32	12
VA	284	136	64
WV	120	164	24
KY	4	20	0
total	548	528	168

502, 503, and 506 were most common. For Age Class 101-120, forest types 502, 503, and 515 were most common.

The 500 group of FIA Forest Types is broadly defined as Oak/Hickory dominated forests (Service, 2024). More specifically, type 502 is defined as Chestnut Oak dominant forest; type 503 is defined as White Oak / Red Oak / Hickory dominated forest; type 506 is defined as Yellow-poplar / White Oak / Red Oak dominant forest; and type 515 is defined as Chestnut Oak / Black Oak / Scarlet Oak dominant forest (Service, 2024).

Though type 515 was more common in the 101-120 age class, type 506 was only marginally less represented than type 515. Given this slim difference, this thesis project opted to use 506 such that the results could exist in a uniform matrix where all three Age Classes include the same three Forest Types and vice versa. In addition, Yellow Poplar is a significant component to regional species composition and timber outputs.

Creating a Representative Sample Population

Using the total number of plots and their respective representation, divided among the six states, a representative sample was created (*Table 2*). A total sample size of 100 plots was chosen for each block in the 3 x 3 (three Age Classes and three Forest Types) matrix. The representation of each state was determined as:

$$\frac{X}{Y} = \frac{A}{B}$$

Where:

X = number of plots per matrix block per state

Y = total number of plots per matrix block from all states

A = number of sample plots per matrix block per state (the variable to be solved)

B = total number of sample plots per matrix block from all states (n =100)

Table 2: Sampled Number of FIA Forest Plots Matching Forest Type and Age Class Sorting Combinations by State (Brackets Used in FVS Simulations)

Age Class: 60-80			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	25	22	23
GA	19	14	9
NC	12	6	21
VA	24	9	20
WV	11	17	13
KY	9	31	14
total	100	100	100
Age Class: 81-100			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	11	25	14
GA	15	9	19
NC	22	10	27
VA	37	25	26
WV	15	22	11
KY	1	9	3
total	100	100	100
Age Class: 101-120			
State	Forest Type: 502	Forest Type: 503	Forest Type: 506
TN	9	20	19
GA	9	13	21
NC	8	6	7
VA	52	26	38
WV	22	31	14
KY	1	4	0
total	100	100	100

A randomizer was used to extract “plot_ID” numbers from the total number of plots in their calculated proportions from each state, Age Class, and Forest Type combination.

Summary of Data Sorting Process

The final outcome of this data sorting process was a list of randomized FIA subplots that were sorted by the geographical counties of the study area; only of sensitive Age Classes; in the most common hardwood Forest Types; and reduced to be proportionally representative of the geographic area they were pulled from. The data was refined through these steps to most broadly address the potential economic and ecological impacts of applying deferred harvest carbon storage agreements to southern Appalachian hardwood forests. After these sorting processes, the data was then ready to be put into FVS simulations.

The brackets by which the data was ultimately sorted were only for simulation purposes. These brackets were only used such that each Forest Type and Age Class combination proportionally drew plots from the determined study area. The more area a state had in the determined southern Appalachian hardwood forest region; the more plots were drawn from that state (*Table 1*). These brackets were eventually dissolved such that trends were only observed for the Forest Type and Age Class combinations and not the state that plots originally existed in.

For convenience, the Forest Type and Age Class definitions were renamed for the rest of this document as follows:

Age Class 60 - 80 = “Approaching Mature”

Age Class 81-100 = “Mature”

Age Class 101-120 = “Slightly Over-Mature”

Forest Type 502 = “Chestnut Oak”

Forest Type 503 = “White Oak / Red Oak / Hickory”

Forest Type 506 = “Yellow-poplar / White Oak / Red Oak”

FVS Model Building

After the final sorting and randomized selection of FIA subplots, the final brackets of subplots (*Table 2*) were grouped into individual simulation runs in the FVS program. The FVS modeling software has been adapted to accommodate FIA subplots through the FIA to FVS conversion manual (Shaw, 2008). Traditional FVS simulations require detailed, proprietary data samplings. The FIA subplots already contain everything required by this proprietary sampling and are automatically converted to FVS format. A simple queuing system to recall this information based on the “plot_ID” attribute is included in the FVS software interface (Shaw, 2008). By uploading the same SQL databases that the sorted and randomized plots were sourced from, the FVS interface can queue subplots by “plot_ID” and pull in all appropriate data needed for simulations. This allowed for ease in the setup of simulation runs in the FVS software. All needed information for a simulation bracket run was imported using only the randomized (but bracket specific) number of corresponding “plot_ID’s.”

Modeled Carbon Storage Agreement Parameters

In order to define the theoretical voluntary carbon storage agreement to be simulated in FVS, the common parameters of real voluntary forest carbon storage agreements were referenced. This thesis project was concerned with the forest behavior under carbon credit agreements rather than the details of applying one specific agreement type. The simplified carbon agreement used for this model chose to consider agreement length and parcel size as determinants of forest behavior. For agreement length both the compliance minimum (100 years) and the recommended voluntary minimum (40 years) were considered (Kreye, 2023). As a compromise of these two minimums, a 50-year carbon storage agreement interval was chosen. While shorter or longer voluntary agreements exist, this choice had several justifications. The first was that a 50-year agreement interval would innately include behaviors for shorter agreements (including the current voluntary

minimum) without greatly surpassing them the way a compliance agreement interval would. Second, 50-years is half of the compliance minimum; using the 50-year agreement interval acts as a preview of possible effects from longer agreements. Lastly, a 50-year interval respects the modeling capabilities of FVS. While FVS is rated for longer simulation durations, this duration chosen is well within its capabilities and should yield higher confidence results (Dixon, 2002). The duration chosen represents a plausible agreement length for southern Appalachian hardwood voluntary carbon storage agreements while also commenting on the longer and shorter agreements available.

The parcel size chosen for the theoretical carbon agreement was the one-acre scale. Due to the limitations of using FIA subplot data, a larger scaling was not possible. Using the one-acre scale already required the 1/24-acre subplot to be scaled up 24X to represent one-acre parcels. While this scaling respected standard forestry conventions where a 1/24-acre plot is an adequate enough sampling to represent one-acre of forest, scaling past this would quickly surpass standard conventions (Henning & Mercker, 2009). Although using a full FIA plot over a single FIA subplot would have offered a larger scaling and parcel size, the single subplot scale offers better sorting specificity as described in the literature review (Shaw & Gagnon, 2019). Given that current voluntary agreements are 1-40 acres in size, the one-acre scale was determined as large enough to predict generalized forest behavior for small parcel forests (Henning & Mercker, 2009) (Keyser, 2023). Larger parcel modeling would have required a different data set or an aggregation of representative data that is beyond the scope of this thesis project. The parcel size chosen was large enough to accommodate a forest modeling project, preserved data specificity, and used an existing, study-area-wide data source.

This parcel scale also affected the decision on management and disturbance within the FVS model. Though FVS is capable of modeling management and disturbance, this project assumed no-harvest and no-disturbance over the 50-year interval. No-harvest, no-disturbance scenarios were chosen to represent the reduced or deferred harvest restrictions that come with forest carbon storage agreements. While management is not excluded from all voluntary carbon agreements, small parcel landowners or managers would likely not have the same management intervention resources as commercial forestry outfits. Rather than quantifying harvest reductions at the one-

acre scale, no-harvest was chosen to simulate the precluded or reduced management likely to be practiced by small parcel forest owners. The no-harvest scenario would be akin to a small parcel landowner entering a carbon storage agreement; leaving the allotted land untouched until the end of the agreement interval; and then looking to use that same untouched land for timber harvest after expiration of the carbon storage interval. No-disturbance scenarios were chosen because natural disturbance is too random to quantify for a project of this scope and scale. Instead, the no-disturbance scenario represents optimistic growth conditions where timber is allowed to grow unbridled and forest change is only from internal growth forces. No-harvest and no-disturbance scenarios were chosen because they allowed for the easiest prediction of forest behavior in deferred harvest carbon storage agreements and their application would have been redundant at the scale chosen for this thesis project.

Refining FVS Software Simulation with “Keywords”

With unaltered conditions, most of the default FVS settings were appropriate for use. However, some “Keywords” were used to make all of the plot simulations congruent with one another (Van Dyck, 2000). This congruence was needed to evenly apply the regional data and sensitivity analyses. Otherwise, the simulation runs would have been mismatched and the model would not have been applicable.

By default, FVS uses the recorded year for which an FIA subplot was last sampled as the starting year for its simulation modeling (Van Dyck, 2000). The many plots used in this project had a variety of sampling years. To rectify this difference, the (SETMODELYEAR) keyword was used. This keyword tells the modeling software to ignore true sampling year and instead to use a user defined starting year (Van Dyck, 2000). For the purposes of this thesis project, the initial model year was set at 2023; this made all plots behave as if they had been last sampled at the same time. While truly sampled in different years, this keyword allowed dissimilarly sampled forest plots to be set at a baseline and grown together congruently. Otherwise, the 50-year interval would have had different timelines for each individual subplot.

Also, regarding simulation years, FVS uses a default interval cycling scheme based on individual plot characteristics; important inventory years can be different for each individual subplot (Van

Dyck, 2000). This was problematic because this project was looking to explore each plot's behavior over time. Consistent intervals were needed to equally compare each plot's behavior. To fix this issue, the (SETCYCLEYEAR) keyword was used ten times to ensure that information was always provided for the years 2023, 2028, 2033, 2038, 2043, 2048, 2053, 2058, 2063, 2068, and 2073 (Van Dyck, 2000). Five-year intervals were chosen as intermediate benchmarks of tracking behavior over time for the 50-year theoretical carbon agreement. Otherwise, each individual subplot would have had different interval years and congruent behavior over time would not have been observable.

The last keyword used was the (NOTRIPL) keyword. Certain parts of the FVS simulation, primarily regeneration and small diameter growth, are stochastic (Van Dyck, 2000). By default, FVS provides multiple stochastic possibilities for this portion of the model. To avoid this, the (NOTRIPL) keyword was used to force the program to provide a singular average and make all parts of the model deterministic (Van Dyck, 2000). Otherwise, multiple estimates for growth would have been given in the simulation results. This would have disrupted the data format because only one estimate per subplot was needed to model value and behavior.

FVS Simulation Outputs

With all of these keywords set, the selected subplots brackets were simulated under a 50-year, deferred harvest, and zero disturbance scenario. After the simulation runs, two tables were exported from FVS to be used in the rest of the model.

The exported table used for timber growth was "Tree_List_East" which contains individual tree data by "plot_ID" and year (Dixon, 2002). This table contained all of the relevant tree level attributes needed to calculate individual subplot timber value. This table uses the "TPA" or tree-per-acre attribute to convert a 1/24-acre FIA plot to a one-acre forest stand (Shaw, 2008). At default, all recorded trees started at 24 trees per acre, a direct scaling of 24X the base plot. The same was true for regeneration where the regen plots are a 1/300-acre plot, are directly scaled at 300X the base plot, and constitute 300 seedlings per acre (Shaw, 2008). The size and count of all trees, in every subplot, and for every interval year is included in the "Tree_List_East" table. This

table allowed for regional data and sensitivity analysis data to be applied to each individual tree and ultimately subplot such that timber value could be tracked for every year over the interval.

The exported table used for carbon storage growth was “FVS_Carbon” which contained carbon volume estimates for various pools of forest carbon (Dixon, 2002). The important attribute from this table was the “total_stand_carbon.” This attribute is a full carbon estimation that includes aboveground, belowground, tree, and herbaceous stock. Unlike the “Tree_List_East” table, the “FVS_Carbon” table was already converted to a per acre basis (Shaw, 2008). The amount of carbon in every subplot and for every interval year is covered by the “total_stand_carbon” attribute. This attribute allowed for regional data and sensitivity analysis data to be applied to each individual subplot carbon estimation such that carbon value could be tracked for every year over the interval.

These two tables were the base for calculating stand value in this project. They are root predictions of timber and carbon growth that later had regional data and sensitivity analysis data applied to them to create value over time dynamics for the carbon storage agreement interval.

Additional Data Outside of FIA or FVS

The simulation results from FVS were only estimations of timber and carbon growth. Additional data was needed to assign values to subplots and apply sensitivity analyses. This additional data described are added metrics that converted growth predictions to regionally appropriate and voluntary carbon market relevant predictive trends.

Grouping of Tree Species

The first additional data source used was a secondary grouping of forest tree species. All species in the FIA data include an identifying species code. For the purposes of applying timber value to these various species, they were grouped by code into product groups according to advice from a regional timber procurement forester (*Table 3*) (Ratliff, 2023). These groupings included all species found in the sampled plots; a full list of this sorting is included in the Appendix.

Definitions for the sorted species codes can be found in FIA’s “Host Trees Species Codes” document (Environmental Monitoring & Assessment Program, 2005). Instead of having a timber price per unit for every possible species in every possible product class, this grouping allowed for a generalized, but regionally appropriate, timber price to be applied to species of similar morphology. These groupings were done either by sorting overarching Family, Genus, or possible product classes. This method is more akin to how timber is valued for harvest in the southern Appalachian hardwood region and is a more appropriate estimation of value than valuing trees by individual species (Ratliff, 2023).

Regional Timber Pricing

This grouping described above was created to work with a verified, regional timber pricing scheme. The timber prices were as reported by, and with the permission of, TimberMart-South (TimberMart-South, 2023). The prices provided by TimberMart-South were provided in price per ton of timber and increased with the quality of timber. FVS reported volume for saw logs in board feet and volume for pulp logs in cubic feet. The prices from TimberMart-South were converted from price per ton to price per board foot for sawlogs and price per cubic foot for pulp trees using TimberMart-South’s proprietary conversions (*Table 3*) (TimberMart-South, 2023).

Timber was sorted into either “pulp” or “timber” classifications (*Table 4*). The diameters for hardwood pulp, hardwood, saw, softwood pulp, and softwood saw were provided by the FVS Southern Variant Manual and used to determine product classes and quality within product classes (FVS Staff, 2008). For saw timber, value (Low, Medium, and High) was assigned based on DBH (*Table 5*). The greater the DBH, the greater the quality or value. Assigning graded values based on tree species and DBH was done previously in work by Prestemon et al. (1998). The timber prices and conversions provided by TimberMart-South are regionally appropriate and what southern Appalachian hardwood forest landowners would receive as stumpage price for their cut timber.

Table 3: Converted Prices from TimberMart-South by Species and Quality: Price per Board Foot in Saw Log Quantity and Price per Cubic Foot in Pulp Quantity (TimberMart-South, 2023)

Species	Quality		
	Low	Medium	High
Ash	\$0.16/BdFt	\$0.19/BdFt	\$0.22/BdFt
Cherry	\$0.19/BdFt	\$0.20/BdFt	\$0.21/BdFt
Maple	\$0.18/BdFt	\$0.20/BdFt	\$0.23/BdFt
Hickory	\$0.18/BdFt	\$0.20/BdFt	\$0.22/BdFt
Red oak	\$0.24/BdFt	\$0.30/BdFt	\$0.37/BdFt
White oak	\$0.28/BdFt	\$0.34/BdFt	\$0.41/BdFt
Walnut	\$0.20/BdFt	\$0.23/BdFt	\$0.26/BdFt
Sweetgum	\$0.17/BdFt	\$0.20/BdFt	\$0.23/BdFt
Yellow poplar	\$0.18/BdFt	\$0.25/BdFt	\$0.31/BdFt
Palletwood	\$0.06/BdFt	\$0.07/BdFt	\$0.08/BdFt
Virginia pine	\$0.07/BdFt	\$0.08/BdFt	\$0.10/BdFt
Hardwood pulp	\$0.18/CuFt	-	-
Softwood pulp	\$0.13/CuFt	-	-
Seedling	\$0	\$0	\$0

Table 4: Product Diameter Cutoffs Derived from FVS Southern Variant (FVS Staff, 2008)

Product	Minimum DBH	Maximum DBH
Hardwood Saw	12"	-
Softwood Saw	10"	-
Hardwood Pulp	6"	12"
Softwood Pulp	4"	10"

Table 5: Product Quality Cutoffs Derived from FVS Southern Variant and Reed Ratliff (FVS Staff, 2008) (Ratliff, 2023)

Quality	DBH
Low	3"-16"
Medium	16"-24"
High	24"+

Carbon Price Sensitivity

To create a carbon sensitivity, three different carbon prices per ton were included in this project. The first price included was \$10/per ton of CO₂ sequestered. This is approximately the average voluntary carbon price in forest carbon storage agreements in 2023 (Forest Trends' Ecosystem Marketplace, 2023). At the start of this project, landowners entering a carbon storage agreement in the southern Appalachian hardwood region would have likely been offered a price close to this.

The second price included was \$50/per ton CO₂ sequestered, approximately the 'social cost of carbon' reported by the White House (United States Government, 2021). As determined by the United States Government, the 'social cost' of carbon is a momentary conversion of the detrimental effect on society one ton of CO₂ being emitted into the atmosphere has.

This price was included to see if carbon storage agreements in southern Appalachian hardwood forests could be profitable when operating at the determined detriment to society rate.

The final price included was \$100/per ton CO₂ sequestered, the approximate average price of carbon traded on the EU emissions trading systems (World Bank, 2023). The EU emissions price is the average price the European Union voluntary carbon storage market operates at. This price was included to see if carbon storage agreements in southern Appalachian hardwood forests could be profitable when operating at the determined European market rate.

These chosen carbon prices are common values applied in forest carbon agreements; the decision to include them was to show how different prices would affect the final value of the simulations. Sensitivity to a higher carbon price would suggest that current voluntary carbon agreements are being undervalued in the region.

Discount Rate Sensitivity

To create a discount sensitivity, three different discount rates were included in this project. The first discount rate used was 0%. The use of a 0% discount rate focused on separating base growth

predictions from the time value of money. This discount rate was used as baseline and point of comparison showing that a growing forest accruing carbon might not always be gaining value.

The second discount rate used was 3%. This discount rate was a rounded value of the average inflation rate over 60 years in the United State, as provided by the Bureau of Labor Statistics (Bureau of Labor Statistics, 2024). This discount rate was used to put the theoretical carbon storage agreement simulations in terms of average economic performance. Even if no other forces are present, inflation is a constant that will affect the value of carbon storage agreements over time.

The final discount rate was 10%. This discount rate was a rounded value of the average stock market return as reported by Forbes Magazine (Sullivan, 2024). The use of a 10% discount rate was used to show how the simulation would perform as an investment scenario when compared to other typical investment scenarios. If carbon storage agreements are not able to compete with other time value investments, then more money could be made cutting timber and investing elsewhere.

Desired Outputs and Calculations of Total Plot Values

The results for this project were created by combining the FVS simulation output data with the regional and sensitivity analysis data. The combination of final FVS outputs and additional data are what completed the entire design of the modeling protocol. FVS outputs alone are only growth predictions; combining these FVS outputs with the additional data is what produced observable, predictive trends. The combination of these data sources produced timber values, carbon values, and entire combined plot values. The outputs were also manipulated to observe species composition and product output changes.

Timber Value Calculations

Timber calculations were created by first matching the size and species of the tree to the value and quality chart derived from TimberMart-South (*Table 3*). A separate column in the data was created that was the combined intersection of species sorting, FIA codes; product sorting, pulpwood vs. sawtimber (*Table 4*); and tree quality, a correlation to tree DBH (*Table 5*).

With the assigned prices paired to each tree, the merchantable portion of a tree was then multiplied by the determined price.

FVS reports merchantable timber volume estimations in three different attributes as follows:

1. “s_bd_ft” which is a board foot estimation of lumber volume from the bole of a tree (FVS Staff, 2008).
2. “s_cu_ft” which is a cubic foot estimation of the entire bole of a tree (lumber and trimmed cuttings) (FVS Staff, 2008).
3. “m_cu_ft” which is a cubic foot estimation of the entire volume of a tree (bole and top) (FVS Staff, 2008).

For saw log trees, value estimation was in two parts. The lumber portion of the tree, as reported by FVS in the “s_bd_ft” column, was multiplied by the assigned price. To account for the pulp volume in the top of a saw log tree, the difference between “m_cu_ft” and “s_cu_ft” was taken and multiplied by the appropriate pulp price. The total value of a saw log tree was the sum of these two values.

For pulp trees, the value estimation was one part. The entire merchantable volume of the tree, or “m_cu_ft”, was multiplied by the determined hardwood or softwood pulp price depending on species.

Both of these values were then multiplied by the associated “TPA” measurement to convert the 1/24-acre FIA subplot to a one-acre forest stand (Shaw, 2008). This conversion abided by standard forest sampling conventions where a 1/24-acre plot is large enough to represent one-acre of forest (Henning & Mercker, 2009). These calculations were for individual trees in a subplot. The sum of all trees calculated in this manner (either saw or pulp calculations) were the total value for a specific subplot at a determined interval year. Summing and scaling the trees within the subplot in this manner made values comparable with the carbon calculations which were already at the one-acre scale (Shaw, 2008).

These calculations were done at every five-year interval mark along the entire 50-year theoretical carbon storage agreement. The final calculations were raw timber values over time for the carbon agreement length. Timber value calculations are as follows:

$$TV_{Saw} = [V_{(s_bd_ft)} * (\$/species/quality) + V_{(m_cu_ft - s_cu_ft)} * (\$/species)] * TPA$$

$$TV_{Pulp} = V_{(m_cu_ft)} * (\$/species) * TPA$$

$$TV_{total} = \sum TV_{Saw} + \sum TV_{Pulp}$$

Where:

TV_{Saw} = Timber Value of Saw Log

TV_{Pulp} = Timber Value of Pulp Log

$V_{(s_bd_ft)}$ = Board Foot Volume of Saw Log

$V_{(m_cu_ft - s_cu_ft)}$ = Cubic Volume of Saw Log Top

$V_{(m_cu_ft)}$ = Cubic Volume of Pulp Log

TPA = Trees Per Acre Conversion Rate

$(\$/species/quality)$ = Unit Value of Saw Logs by Species and Quality in Price per Board Foot

$(\$/species)$ = Unit Value of Pulp Logs by Species in Price per Cubic Foot

TV_{total} = Total Timber Value, Sum of All Trees in Scaled Plot

Carbon Value Calculations

Carbon calculations for each interval were created by multiplying the difference between the initial (“total_stand_carbon”) and the interval year’s (“total_stand_carbon”) by the respective carbon price per ton values described in the carbon sensitivity section. This value was then multiplied by 3.67 or the conversion factor between tons of elemental carbon stored in the forest and tons of CO₂ sequestered (Romm, 2011). Trees store elemental carbon but sequester CO₂ from the atmosphere. The value of carbon is in terms of tons of CO₂ sequestered. Thus, elemental stored carbon was converted into tons of CO₂ sequestered. Stand carbon was reported in an already converted per/acre volume from FVS and did not need to be scaled by TPA like timber values.

These calculations were for entire FIA subplots. Calculating carbon values in this manner (unscaled) made values comparable with the scaled timber values (Shaw, 2008). These calculations were done at every five-year interval mark along the entire 50-year theoretical carbon storage agreement. The final calculations were raw carbon values over time for the carbon agreement length. Subplot carbon values calculations are as follows:

$$TCV = (TSC_n - TSC_i) * 3.67 * (\$ \text{ of CO}_2/\text{ton})$$

Where:

TCV = Total Carbon Value at Interval year

TSC_n = Total Stand Carbon at Interval Year in Elemental Carbon

TSC_i = Total Stand Carbon at Initial Year in Elemental Carbon

3.67 = The Conversion Rate Between Elemental Carbon in Trees and Carbon Dioxide
Sequestered

$$\text{\$ of CO}_2\text{/ton} = \text{Value per Ton of Carbon Dioxide Sequestered}$$

Final Subplot, Timber, and Carbon Values

The total value of a subplot was defined as the sum of accrued carbon value and scaled timber value. Total value was important for this thesis project as it was the determining factor of profitability. The competition of independently behaving timber and carbon values combining to create a final value was the tradeoff dynamic this thesis project was hoping to observe. If the value gained by accruing carbon combined with the potential value lost from degrading timber was still modeled at an overall increase, then carbon storage agreements would be profitable for southern Appalachian hardwood landowners. If this combined value was modeled at an overall decrease, then carbon storage agreements would not be profitable for southern Appalachian hardwood landowners.

Final values, as well as independent timber and carbon values, were created for every five-year interval during the 50-year theoretical carbon agreement. To put these values into both stock growth and real-world economic scenarios, the calculated values were put into the Net Present Value equation using the discount rates described in the discount sensitivity section. The NPV equation allowed for value to be tracked over time while respecting time values of money and observing potential for loss in value. The NPV equation was also applied to independent timber and carbon values to determine how the individual parts of total value behaved in the tradeoff relationship. The NPV calculations are as follows:

$$\text{NPV}_{\text{Total}} = (\text{TTV}_n + \text{TCV}_n) / [(1 + i)^n]$$

$$\text{NPV}_{\text{Timber}} = (\text{TTV}_n) / [(1 + i)^n]$$

$$\text{NPV}_{\text{Carbon}} = (\text{TCV}_n) / [(1 + i)^n]$$

Where:

$$\text{NPV}_{\text{Total}} = \text{Net Present Value of Timber and Carbon Value}$$

NPV_{Timber} = Net Present Value of Timber Value

NPV_{Carbon} = Net Present Value of Carbon Value

TTV_n = Total Timber Value at Interval Year

TCV_n = Total Carbon Value at Interval Year by Carbon Sensitivity Price

i = Discount Rate by Discount Sensitivity

n = Interval Year

Normalization of Subplot and Timber Values

The final value calculations used for this project initially created results in terms of absolute value over time. While still valid modeling results, a large variation in initial subplot values made overall trends hard to observe from these absolute value results. This absolute value presentation was problematic because this thesis project was concerned with change in subplot value over time rather than initial value of subplots.

To correct these observations, final subplot values and timber values were normalized to reframe absolute value over time to change in value over time. Initial values were set to zero and any change in value was observed from the zero baseline. Independent carbon values were excluded from this normalization because no value was given to existing carbon stocks in the subplots. Value was only assigned to accrued carbon storage over time and was thus already in terms of change in value over time. The normalization calculations are as follows:

$$NNPV_{\text{Subplot}} = TSV_n - TSV_i$$

$$NNPV_{\text{Timber}} = TTV_n - TTV_i$$

Where:

$NNPV_{\text{Subplot}}$ = Normalized Net Present Value of Subplot (Timber and Carbon Values)

$NNPV_{\text{Timber}}$ = Normalized Net Present Value of Timber

TSV_n = Total Subplot Value at Interval Year

TSV_i = Total Subplot Value at Initial Year

TTV_n = Total Timber Value at Interval Year

TTV_i = Total Timber Value at Initial Year

Importance Value

Potential species composition change from the deferred harvest carbon storage agreement modeling was observed using the “Importance Value” metric. Importance Value is a measurement of a species’ prevalence across a landscape or sampled area. Importance Value or “IV” is a scale out of 300 where the Relative Frequency of a species in **all** plots accounts for 100; the mean Dominance of a species in **each single** subplot plot accounts for 100; and the mean Density of a species in **each single** subplot accounts for 100 (Curtis & McIntosh, 1951). The three summed scores represent the Importance Value of a species from sampled plots. Frequency was already expressed as the average of all subplots sampled; Dominance and Density were converted to averages to match Frequency and make statements about the averages of similar subplots.

Instead of tracking Importance Value for every individual species within the subplot data, important target species were grouped by family or genus into target species groups. The grouped species classes chosen were Red oak, White oak, hickory, Yellow-poplar, and maple; these groupings were based on the most valuable or common target species in southern Appalachian hardwood forests. With species grouped, frequency, dominance, and density were calculated at the species grouping level

The results of this calculation yielded the average Importance Value of target group species for every Forest Type by Age Class combination. Importance Value was observed at five-year intervals for the entire 50-year theoretical carbon agreement the same as subplot values. The Importance Value calculations were used to observe potential change in prevalence of target species groups over time. This potential change is how mesophication and in part products output change was observed in the subplot simulations. The Importance Value calculations are as follows:

$$RFR = \frac{\text{Number of Occurrences of a Species Groupings in all Subplots}}{\text{Total Number of Subplots}} \times 100$$

$$MRDM = [\sum (\frac{\text{Sum of Basal Area of Trees in a Species Grouping in a Subplot}}{\text{Sum of Basal Area of All Species in a Subplot}} \times 100)] / 100$$

$$MRDN = [\sum (\frac{\text{Sum of Count of Trees per Acre by Species Grouping in a Subplot}}{\text{Sum of Count Trees Per Acre of All Species in a Subplot}} \times 100)] / 100$$

$$IVI = RFR + MRDM + MRDN$$

Where:

IVI = Importance Value Index of a Species Grouping, within a Forest Type and Age Class Combination, at Determined Interval Year

RFR = Relative Frequency of a Species Grouping in **All** Subplots, within a Forest Type and Age Class Combination

MRDM = Mean Relative Dominance of a Species Grouping (Averaging **Each Single** Subplot Value), within a Forest Type and Age Class Combination

MRDN = Mean Relative Density of a Species Grouping by (Averaging **Each Single** Subplot Value), within a Forest Type and Age Class Combination

Other Composition and Products Metrics

The other calculations used in this thesis project related to product output. Average DBH was calculated for the same Importance Value species sorting by taking the mean of all trees' DBH within a species grouping for all plots in each Forest Type by Age Class combination. Average amount of pulp volume in cubic feet and saw volume in board feet were calculated. The cubic volume of full pulp trees and saw treetops, as well as the board foot volume of all saw trees, was summed and averaged by Importance Value species grouping for each Forest Type and Age Class combination. All of these values were observed at five-year intervals for the entire 50-year period. These metrics were used to track potential products output change from the subplot simulations. These additional metrics were calculated as follows:

$$MDBH = [\Sigma DBH] / 100$$

$$MSV = [\Sigma SV] / 100$$

$$MPV = [\Sigma PV] / 100$$

Where:

ΣDBH = Sum of Diameter at Breast Height Measurements of all Trees of Species Grouping within a Forest Type and Age Class Combination

ΣSV = Sum of Saw Volume Measurements [$V_{(s_bd_ft)} + V_{(m_cu_ft - s_cu_ft)}$] of all Trees of Species Grouping within a Forest Type and Age Class Combination

ΣPV = Sum of Pulp Volume Measurements [$V_{(m_cu_ft)}$] of all Trees of Species Grouping within a Forest Type and Age Class Combination

$MDBH$ = Mean DBH of a Species Grouping within a Forest Type and Age Class Combination

MSV = Mean Saw Volume of a Species Grouping within a Forest Type and Age Class
Combination

MPV = Mean Pulp Volume of a Species Grouping within a Forest Type and Age Class
Combination

See **Timber Value Calculations** subsection for explanation of volume units.

Coding Calculation of Methodologies

All of the calculations and data sources described above were combined and processed using a framework of R code. The use of R allowed mass calculations to be made for each subsection of the described methodology for every five-year interval over the entire 50-year theoretical carbon agreement. These calculations called for conversion between tree level data and subplot level data as well as the pairing of FVS outputs to regional and sensitivity analyses data. The use of an R code suited allowed these data manipulations to be made quickly and with consistent accuracy. Final results for subplot values, species composition change, and products profile change were created using the outputs of the R code suite. The suite of R code used was a coding translation of all the described methodology. FVS outputs for timber and carbon growth were put into R and all of the post processing value, species composition, and products output methodologies were applied therein. A simplified version of the R coding workflow was as follows;

1. Adding sorted tree level data to R (see **FVS Simulation Outputs** subsection)
2. Assigning values to trees based on species, DBH, and merchantable volumes (see **Grouping of Tree Species** and **Regional Timber Pricing** subsections)
3. Adding subplot level Carbon data to (see **FVS Simulation Outputs** subsection)
4. Converting tree level values to subplot level values (see **Timber Value Calculations** subsection)

5. Combining tree subplot level data and carbon subplot level data to create final subplot values (see **Carbon Value Calculations; Final Subplot, Timber, and Carbon Values; and Normalization of Subplot and Timber Values** subsections)
6. Defining and creating alternate Carbon sensitivity values to create alternate final values (see **Carbon Price Sensitivity** subsection)
7. Defining and creating alternate Discount sensitivity values to create alternate final values (see **Discount Rate Sensitivity** subsection)
8. Creation of Importance Value and Importance Value species groups (see **Importance Value** subsection)
9. Calculating IV and DBH averages (see **Importance Value** and **Other Composition and Products Metrics** subsections)
10. Calculating Product Output averages (see **Other Composition and Products Metrics** subsection)
11. Export R coding calculation tables for creation of results tables and figures

The full suite of R code is available in the Appendix.

Chapter 4: Results and Discussion

Introduction to Chapter Format

The creation of these results suggests that the FIA to FVS methodology is a viable methodology for quantifying southern Appalachian hardwood forests; FIA data and FVS modeling was successfully combined to observe regional forest trends. Likewise, the theoretical deferred harvest carbon storage agreements were successfully integrated into this combination meaning that the economic and ecological effects of these agreements are observable trends using this methodology. Addressing both of these questions means that there are metrics available to predict economic and ecological forest behaviors under deferred harvest carbon storage agreements; these predictions could be used by landowners or stakeholders to determine the viability of these agreements and their willingness to participate in them.

The format of all of the results reflects the 3x3 matrix of the Age Class and Forest Type combinations; each matrix block represents one out of nine total Forest Type and Age Class combinations. Some results were created where one matrix block shows the behavior of all 100 plots within an Age Class and Forest Type combination, while others were created where one matrix block represents the average behavior of those 100 plots within an Age Class and Forest Type combination. Regardless, the adherence to the 3x3 matrix structure was important because this thesis project was designed to observe general, regional trends of frequently occurring hardwood forest in the southern Appalachian region, rather than the behavior of a specific forest or land parcel. These results are only **predictions** of what could happen in deferred harvest carbon storage agreements in southern Appalachian hardwood forests and are not ground truth recordings. Thus, these results are a commentary on potential happenings rather than quantitative measurements of forest behavior. The 3x3 matrix intentionally presents all simulated results in relation to one another. Showing each individual Forest Type and Age Class combination in a combined presentation better shows the results as predictive trends for a whole region rather than each combination having its own presentation. This is why the results and discussion chapter are combined in this thesis project. Since these results were predictions of forest behavior rather than

quantitative recordings, it was best to present the results; discuss what trends they suggest; and acknowledge the advantages or disadvantages of their creation.

Discount Rate Sensitivity

With 50-years of deferred harvest, the modeled stands continued to grow and increased in value by growing timber volume and accumulating carbon (*Figure 3*). An obvious upward trend in value was present in the simulations. The presentation of this format was problematic, however. This study was concerned with observing a change in value; the wide variation in initial value of the forest stands interfered with observing this change. With a large variation in initial values, the starting, ending, and change in values for all the plots was not clear. To fix this presentation, all further results were normalized, where initial stand values were set to zero and change in value (positive or negative) was then observed from a baseline. In (*Figure 4*), the same change in behavior was shown as in (*Figure 3*), only normalized. Though the same general trend of an increase in value was observed, this format better revealed the potential for a loss in value. A normalization of the data eliminated that broad variation of initial stand values and reframed the data to better observe change in value. With normalization, every plot started from the same baseline even if initial plot values were different; starting from the same baseline better showed change over time. The majority of plots increased in value over time, but a few plots dropped below, or remained near to, the zero-line (*Table 6*).

In the no-discount scenario, 98.4% of all plots gained value at an average increase of \$5,245. While initially positive, these no-discount scenarios were optimistic. An undiscounted scenario was not representative of how these plots would be valued in a real carbon storage agreement; in real carbon storage agreements, time value of money must be considered. Discount rates were applied to the plot growth models to put the simulations in terms of real carbon agreements where money would innately devalue over the agreement interval. The additions of these discount rates converted the simulations from simulations predicting forest growth to simulations predicting economic change. When a 3% discount rate was applied to the future forest's values, the general value trends were reversed; most stands lost value over the 50-year time frame. (*Figure 5*) (*Table 7*)

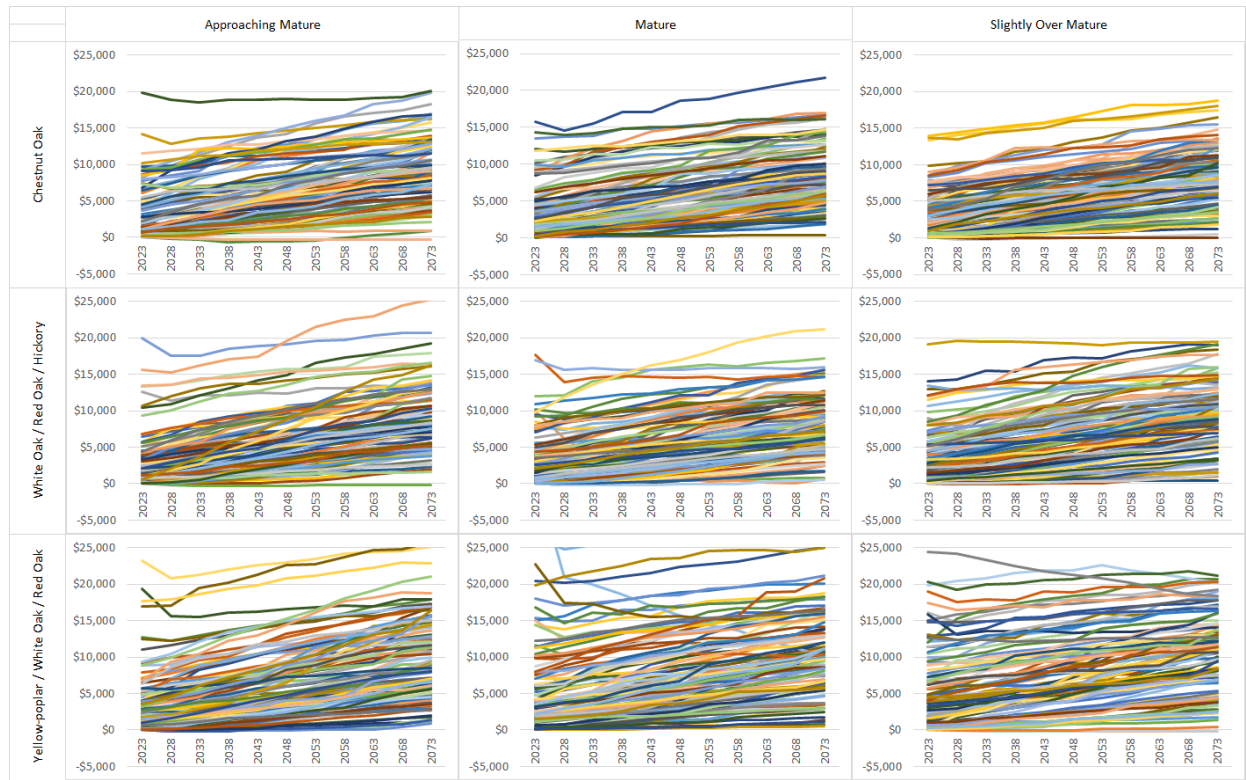


Figure 3: All 900 Plots Absolute Value of Timber Stands Sorted by Age Class and Forest Type:
Carbon price = \$10/ton, Discount Rate = 0%

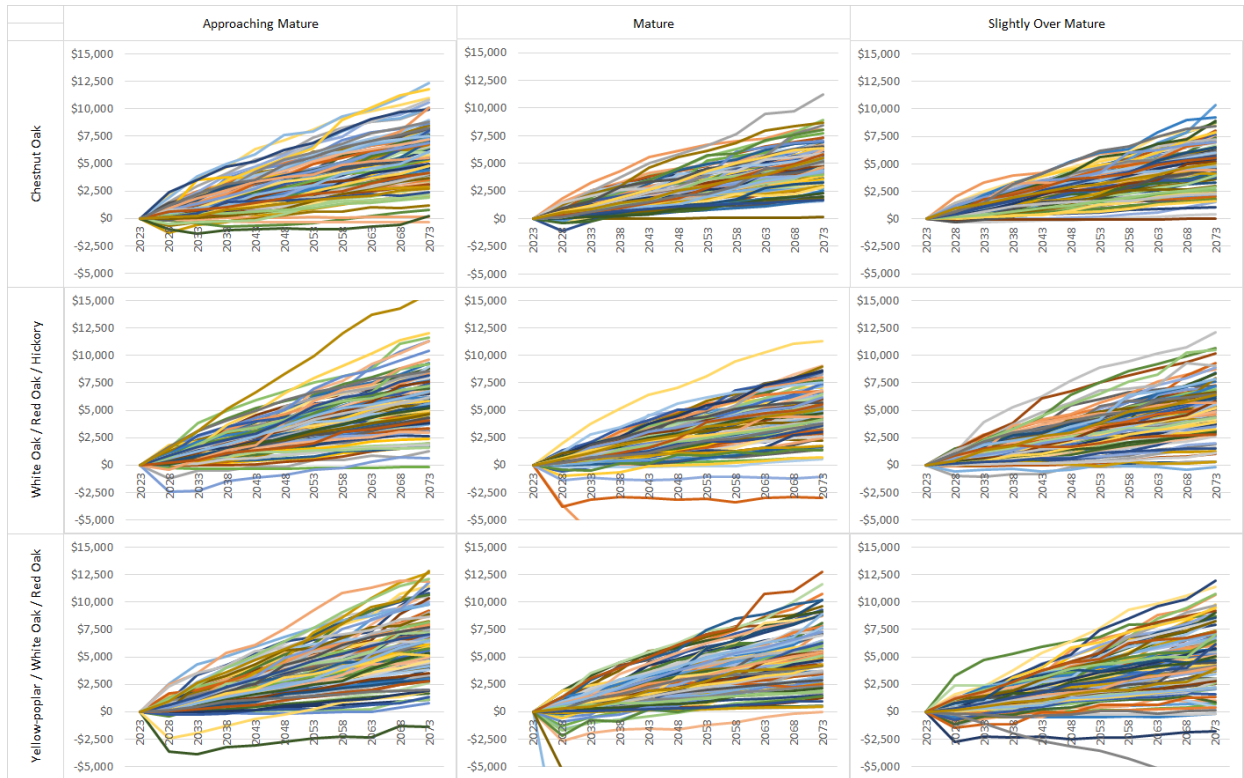


Figure 4: All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 0%

Table 6: Summary Statistics for All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 0%

	Approaching Mature		Mature		Slightly Over Mature	
Chestnut Oak	mean	\$5,615	mean	\$4,825	mean	\$5,111
	positive	99	positive	100	positive	100
	negative	1	negative	0	negative	0
White Oak / Red Oak / Hickory	mean	\$5,748	mean	\$4,718	mean	\$5,267
	positive	99	positive	97	positive	99
	negative	1	negative	3	negative	1
Yellow-poplar / White Oak / Red Oak	mean	\$6,122	mean	\$4,843	mean	\$4,957
	positive	99	positive	97	positive	96
	negative	1	negative	3	negative	4

In (Figure 5), the same growth scenario was modeled but with a 3% yearly discount applied to represent inflation. Even with base inflation applied, the trend in value completely changed. Despite the plots continuing to grow, increasing in nominal value and accruing carbon, the value growth was not enough to keep up with 3% inflation. Plots that were once positively trending, leveled off and decreased in value; more plots dropped below the zero-line indicating a loss in value. The plots that did not drop below zero instead came closer to straddling the zero-line indicating a minimal increase in value; nearly all increases in value were below the average increase of the no-discount growth scenarios. The difference between the no-discount and inflation scenarios was better shown through comparison of their statistics. When accounting for inflation, 62.3% of all plots lost value in this scenario. The average loss of all stands was - \$1,831.

This discount sensitivity was more apparent when observed in (Figure 6) where the stands were modeled at a 10% per year discount rate to simulate the forests as an investment opportunity. When compared against the expected average stock market return, the forest plots overall decreased in value more significantly than in the inflation simulations (Table 8). The plots were already unable to keep up with discount from inflation; the increase to a stock market return made this inability even more drastic. The trend in change in value plummeted further such that nearly all stands lost value by dropping below the zero-line. Some stands continued to straddle the zero-line but with no significant increase in value.

For plots modeled against a stock investment, there was a 98.1% chance of losing money; this was a 35.8% increase in likelihood of losing money from the base inflation scenario. The average loss at this discount was -\$3,844, over double that of simulations discounted at inflation. If forest carbon agreements in the region were to be used as investment opportunities, these results suggest it would be nearly impossible to make money; it would be a better investment to cut timber and allocate the money elsewhere as opposed to keeping timber in a carbon storage agreement.

The findings of this sensitivity analysis suggest that forests will keep growing and adding carbon storage; this result would be an initially positive finding for landowners and stakeholders

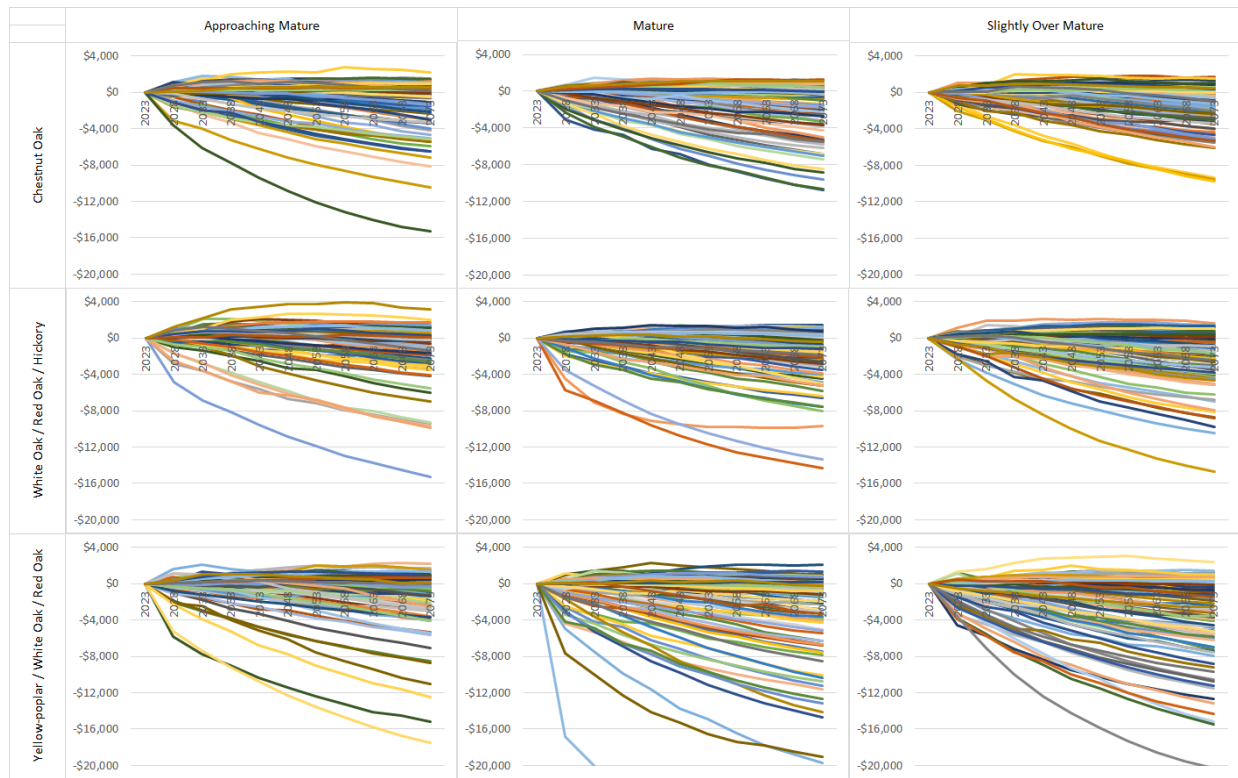


Figure 5: All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 3%

Table 7: Summary Statistics for All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 3%

	Approaching Mature		Mature		Slightly Over Mature	
Chestnut Oak	mean	-\$1,151	mean	-\$1,660	mean	-\$1,400
	positive	51	positive	33	positive	34
	negative	49	negative	67	negative	66
White Oak / Red Oak / Hickory	mean	-\$977	mean	-\$1,572	mean	-\$1,876
	positive	48	positive	38	positive	33
	negative	52	negative	62	negative	67
Yellow-poplar / White Oak / Red Oak	mean	-\$1,465	mean	-\$3,267	mean	-\$3,114
	positive	43	positive	27	positive	32
	negative	57	negative	73	negative	68

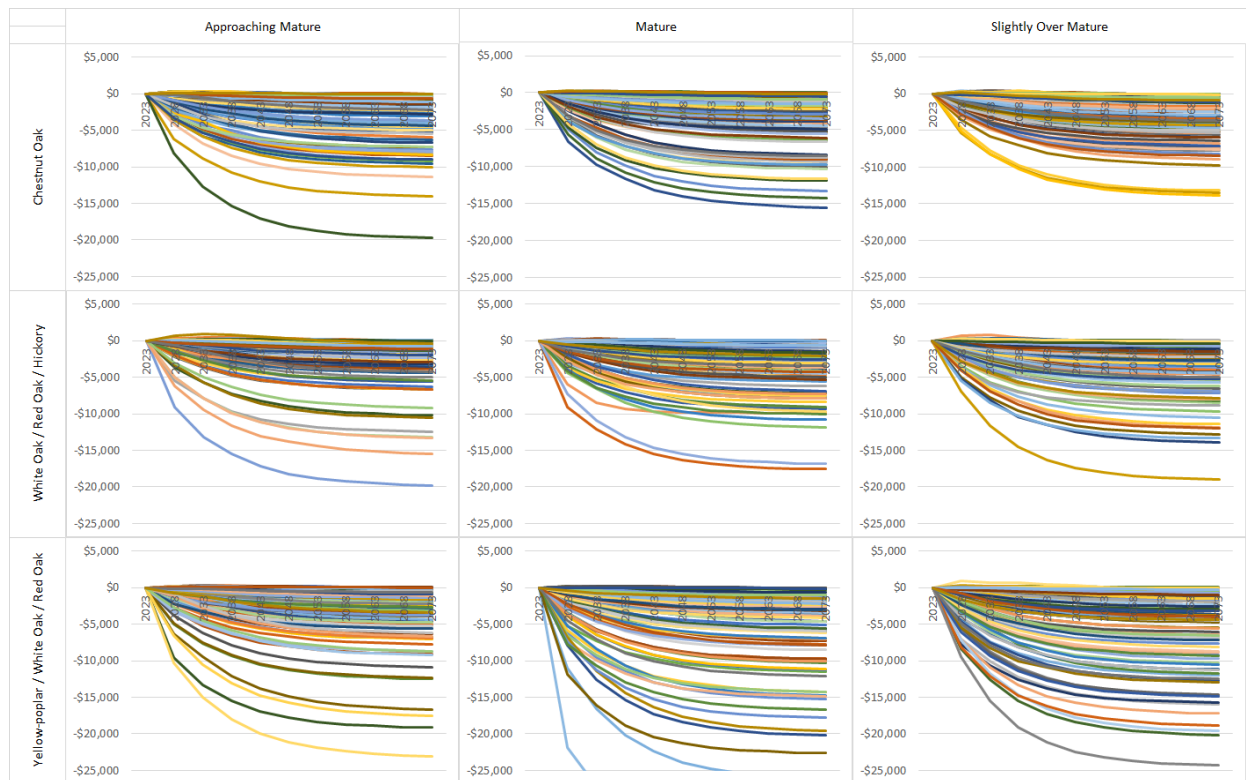


Figure 6: All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 10%

Table 8: Summary Statistics for All 900 Plots Delta Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$10/ton, Discount Rate = 10%

	Approaching Mature		Mature		Slightly Over Mature	
Chestnut Oak	mean	-\$3,076	mean	-\$3,504	mean	-\$3,252
	positive	0	positive	1	positive	0
	negative	100	negative	99	negative	100
White Oak / Red Oak / Hickory	mean	-\$2,890	mean	-\$3,361	mean	-\$3,908
	positive	7	positive	4	positive	1
	negative	93	negative	96	negative	99
Yellow-poplar / White Oak / Red Oak	mean	-\$3,623	mean	-\$5,575	mean	-\$5,410
	positive	3	positive	0	positive	1
	negative	97	negative	100	negative	99

interested in carbon storage agreements. However, when economic parameters were applied to the simulations, this continued growth and storage did not compensate for loss in value. A 3% discount alone was enough to make a majority of the simulations lose value; when increased to a 10% discount, nearly all of the simulations lost value. This means that even under the minimum discount, inflation, the modeled potential to lose money was significant with this potential being nearly absolute in an investment scenario. This finding could be cautionary for landowners and stakeholders wishing to participate in carbon storage agreements.

Carbon Price per Ton Sensitivity

In the averages of the 100 plots in each of the nine simulation blocks, timber was the primary driver of value in the forest stands at the baseline carbon agreement price (*Figure 7*). Carbon was but a fraction of the total value for the stands in an undiscounted scenario. This was partly due to the way this project was set up. In this project, only timber had an initial value. This study only assigned value to carbon accrued and no value was assigned to existing carbon held in the stand. The only way to lose value from carbon was substantial mortality and an overall loss of initial stand value; a negative accrual of carbon and subsequent loss in value was rare throughout any of the simulations.

With carbon at \$10/ton, or the average voluntary carbon credit agreement price, and when discounted at 3% inflation, the return from carbon did little to offset the devaluing of timber from inflation; carbon growth was only able to slightly fight inflation and timber was not able to on average (*Figure 8*). The minimal value gained from accrued carbon did little to offset the depreciation of timber value. While both carbon and timber volumes increased, the monetary values associated with this increase were not enough to keep up with inflation (*Table 7*).

The average voluntary price was used because it was the expected going rate of carbon in storage agreements at the time of this study. However, other institutions, such as the Whitehouse or the EU, cite this price as being too low to make the voluntary market functional. Additional carbon prices were used to observe the behavior of southern Appalachian hardwood forests in carbon storage agreements against other institutions' estimations of value. These were used to determine

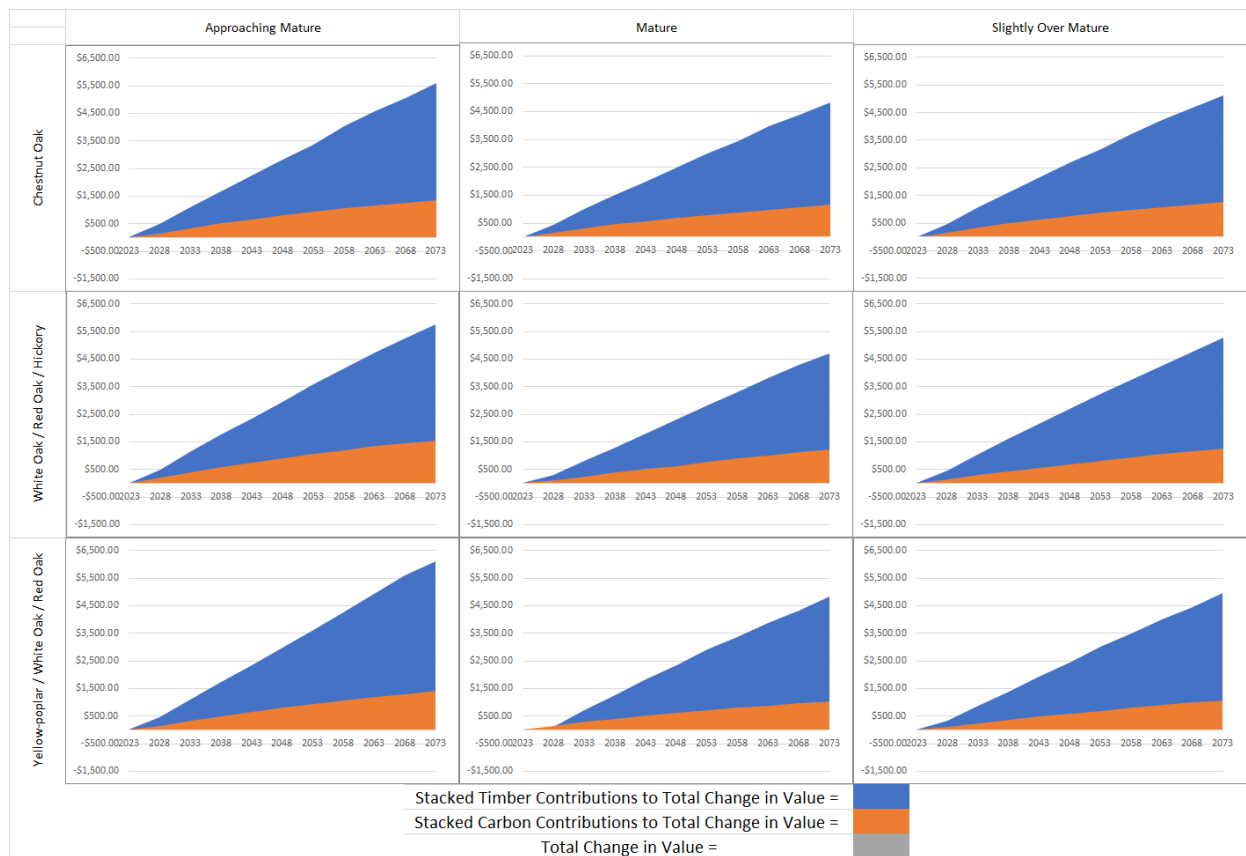


Figure 7: Stacked Average Contributions to Change in Value of Timber Stands by Carbon and Timber Sorted by Age Class and Forest Type; Carbon price = \$10/ton, Discount Rate = 0%

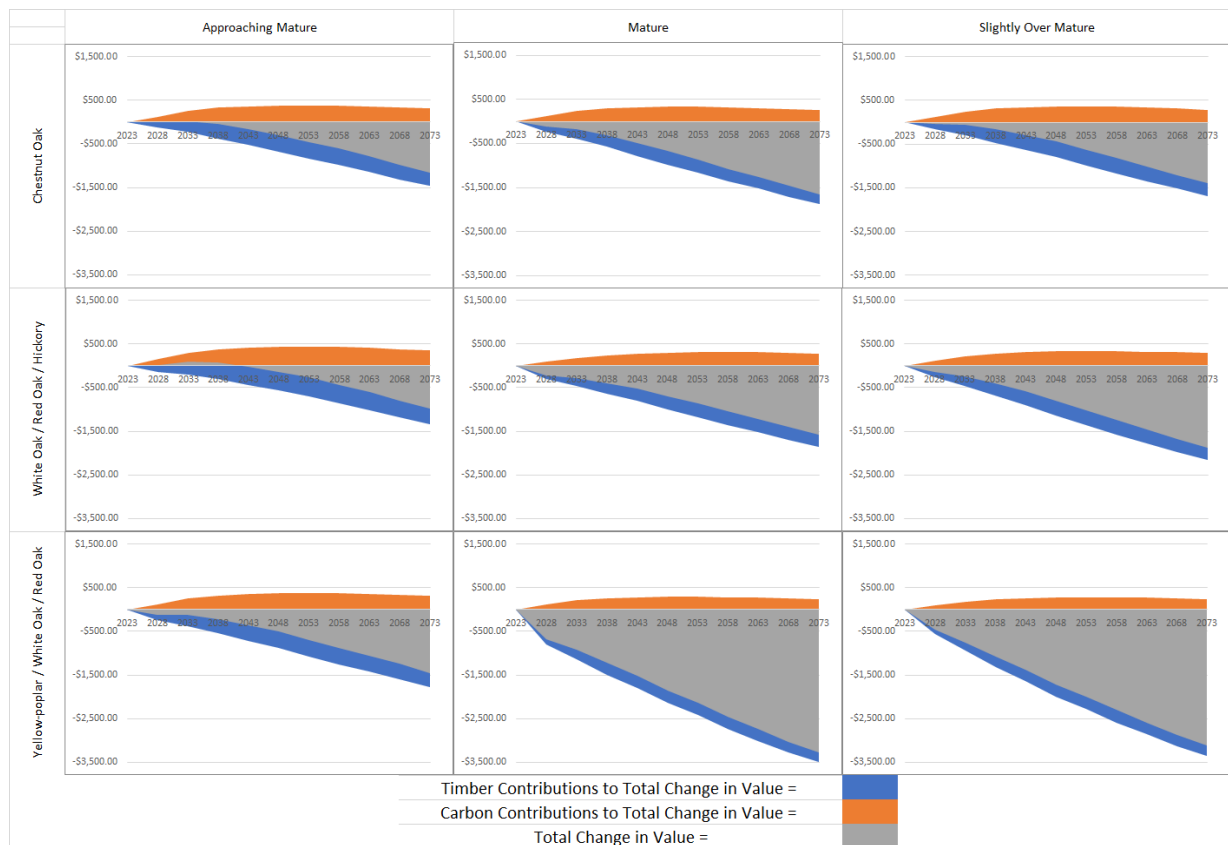


Figure 8: Average Contributions to Change in Value of Timber Stands by Carbon and Timber Sorted by Age Class and Forest Type; Carbon price = \$10/ton, Discount Rate = 3%

profitability against other standards rather than those currently trending in the voluntary market. If the other standards could make the agreements profitable, then this sensitivity would suggest potential viability of carbon storage agreements in the region.

When the carbon price was increased to \$50/ton, or the “social cost of carbon,” more of a tradeoff was observed (*Figure 9*) (*Table 4*). The carbon contribution increased by a factor of five and this increase helped to offset the depreciation of timber value.

Some combinations, such as the “Approaching Mature,” “Chestnut Oak” and “White Oak / Red Oak / Hickory” forests showed a tradeoff where accrued carbon value did offset the timber depreciation. However, at the end of the assumed 50-year period, average value decreased for most cases. During this tradeoff period, the point of maximization was shorter than the period where value was lost; when the trend of total change in value turned negative, maximization was lost. This means that participants in these carbon agreements would still have been losing money even if accrued carbon value was briefly maintaining some kind of tradeoff. The “Approaching Mature” and “Mature,” “Yellow-poplar / White Oak / Red Oak” forests suffered significant losses. Overall, an increase to the social cost of carbon did little to offset timber depreciation. Even at the increased social cost of carbon, there was still a 40.8% chance of losing money with an overall average loss of -\$685 (*Table 9*). While better than the 62.3% chance shown in (*Figure 5*) and detailed in (*Table 7*), this was still a significant chance to lose money.

When the carbon price was increased to the European Union average cost of carbon, \$100/ton, moderate change was observed. The carbon contribution increased by a factor of 10, and this increase did more to offset the depreciation of timber value when compared to a carbon price of \$50/ton or \$10/ton. Most cases showed a positive tradeoff where accrued carbon value did offset the timber depreciation (*Figure 10*) (*Table 10*). In the same way as before, the maximization period was still shorter than the offset period meaning that value was still being lost earlier than the full agreement period. In other cases, such as the “Mature” and “Slightly Over-Mature” “Yellow-poplar / White Oak / Red Oak” forests, the accrued carbon value directly offset timber depreciation for about 40 years before dropping out and declining. This maximum carbon price increased how much value was gained on average and had significant counteracting effects on the force of timber depreciation.

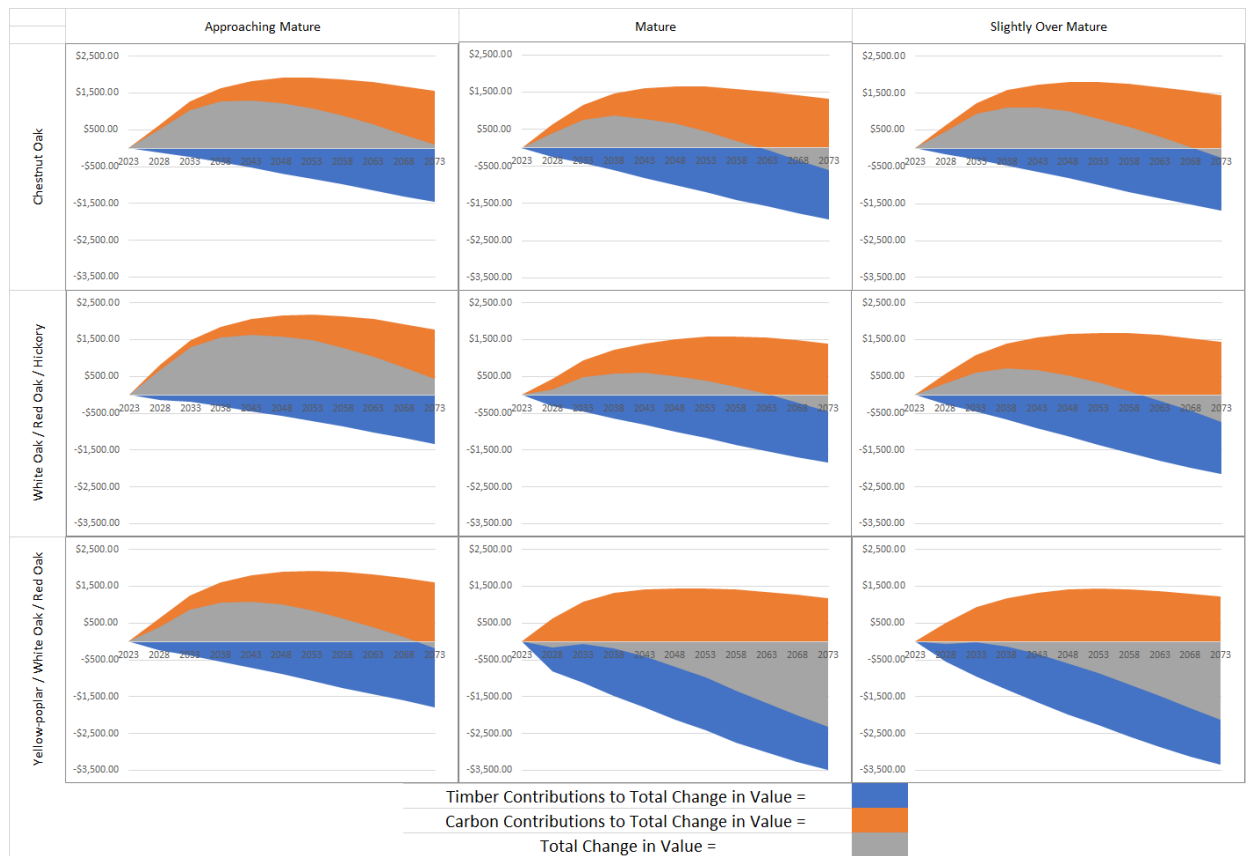


Figure 9: Average Contributions to Change in Value of Timber Stands by Carbon and Timber Sorted by Age Class and Forest Type; Carbon price = \$50/ton, Discount Rate = 3%

Table 9: Summary Statistics for All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type: Carbon price = \$50/ton, Discount Rate = 3%

	Approaching Mature		Mature		Slightly Over Mature	
Chestnut Oak	mean	\$89	mean	-\$610	mean	-\$251
	positive	67	positive	60	positive	60
	negative	33	negative	40	negative	40
White Oak / Red Oak / Hickory	mean	\$444	mean	-\$459	mean	-\$728
	positive	73	positive	60	positive	54
	negative	27	negative	40	negative	46
Yellow-poplar / White Oak / Red Oak	mean	-\$185	mean	-\$2,325	mean	-\$2,136
	positive	64	positive	47	positive	47
	negative	36	negative	53	negative	53

At the EU price, there was only a 30% chance of losing money with an overall average gain of \$749. This was the first sensitivity that showed an average gain besides the undiscounted, average voluntary carbon price scenario.

As suggested by (*Figure 8*), (*Figure 9*), and (*Figure 10*), the change in value for the forest stands was sensitive to assumed carbon price per ton. At the average voluntary price, \$10/ton, carbon was a minor portion of the individual stand values, and timber generally devalued quicker than carbon could accrue. At the social cost, carbon value began to rival timber depreciation but did not fully compensate for loss in timber value. At the EU price, carbon was almost always more valuable than timber depreciation and nearly created tradeoffs for all combination blocks.

At the current voluntary price, carbon storage agreements were modeled at being not profitable. This is significant as landowners and stakeholders currently in or about to engage with storage agreements could be losing or at risk of losing money. The social cost of carbon offset this dynamic slightly and made instances where carbon storage agreements could be profitable. This is significant as the trending social cost of carbon is greater than the operating voluntary price, but even the potential from moving up to the social cost of carbon created marginal room for profitability. The EU price of carbon did the most to offset this dynamic where most simulation combinations ended with value. However, ending with value at the EU price of carbon was not absolute across the board and, even the plots that ended with value were not maximized. Plots ending with value after the interval were still on average losing potential value as the interval pushed them past the point of diminishing returns. This is significant as even the highest carbon cost used did not wholly guarantee an increase in value and consistently lost value if maximization was considered. These results pose an important implication for landowners and stakeholders where the current voluntary price is far below the threshold of profitability for southern Appalachian hardwood forests in carbon storage agreements. If consistent profitability or maximization were also concerns for landowners or stakeholders, the social cost and EU price also failed to fully meet this threshold. Much like the findings of timber value depreciation under discounted scenarios, this finding could be cautionary for landowners and stakeholders wishing to participate in carbon storage agreements.

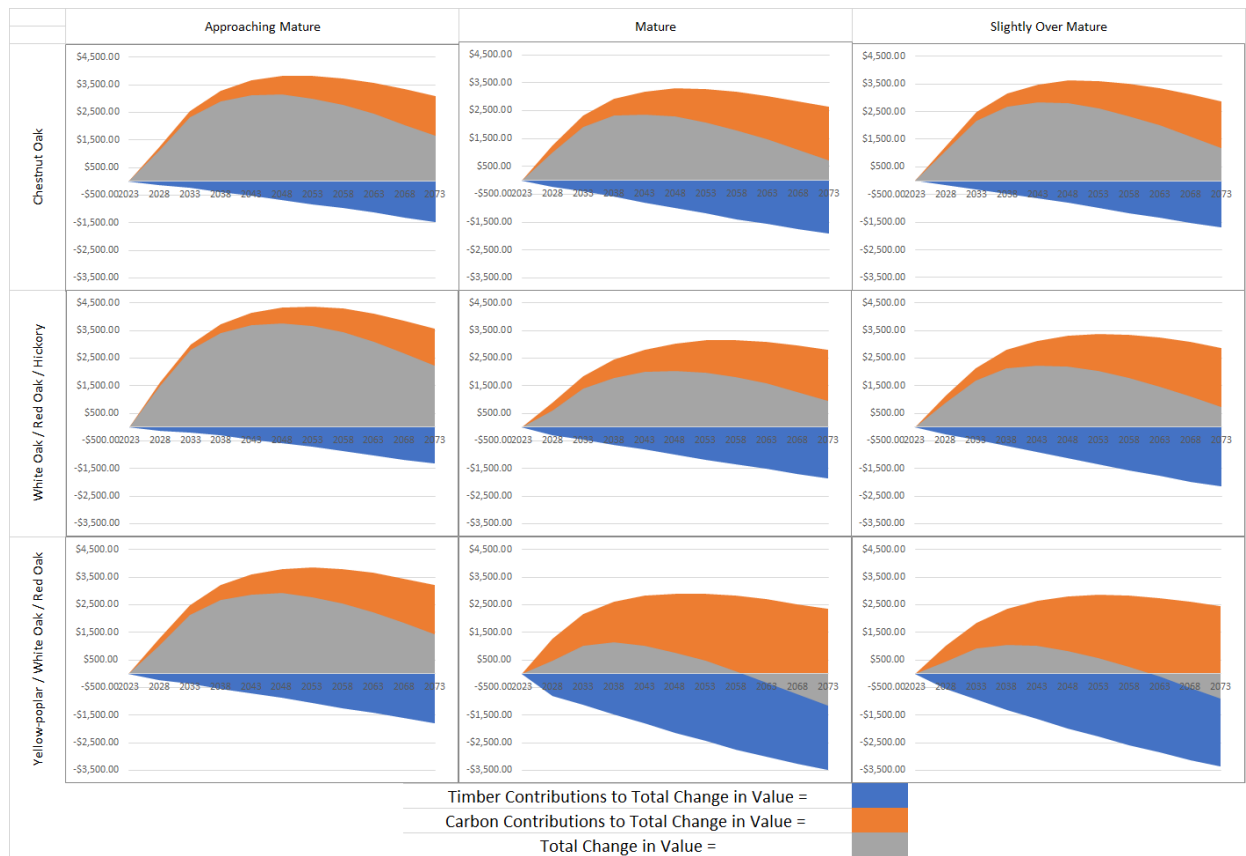


Figure 10: Average Contributions to Change in Value of Timber Stands by Carbon and Timber Sorted by Age Class and Forest Type; Carbon price = \$100/ton, Discount Rate = 3%

Table 10: Summary Statistics for All 900 Plots Change in Value of Timber Stands Sorted by Age Class and Forest Type; Carbon price = \$100/ton, Discount Rate = 3%

	Approaching Mature		Mature		Slightly Over Mature	
Chestnut Oak	mean	\$1,640	mean	\$702	mean	\$1,184
	positive	75	positive	68	positive	72
	negative	25	negative	32	negative	28
White Oak / Red Oak / Hickory	mean	\$2,220	mean	\$933	mean	\$708
	positive	79	positive	75	positive	68
	negative	21	negative	25	negative	32
Yellow-poplar / White Oak / Red Oak	mean	\$1,414	mean	-\$1,146	mean	-\$914
	positive	80	positive	58	positive	55
	negative	20	negative	42	negative	45

Species Composition

Importance Value was used to observe the overall prevalence of target tree species groups in the modeled forest stands. A modeled change in Importance Value suggests a shift in prevalence of a certain species group in a plot and represents a potential negative consequence resulting from carbon storage agreements. For this thesis project, species composition is not a simple root counting of the number of different species existing within an individual plot. Instead, it is a measure of how a certain species group changes in number of occurrences within a plot; amount of area occupied within a plot; and number of occurrences across the entire landscape for which all simulated plots exist as defined by “Importance Value” (Curtis & McIntosh, 1951).

In these results, the Hickory group was modeled to decrease in Importance Value for all of the simulation blocks (*Figure 11*). The Yellow-poplar group also exhibited decline in a majority of the simulation blocks. However, this decline could be more attributed to succession where pioneer species tend to transition to more shade-tolerant species. The most important dynamic modeled in (*Figure 11*) was the interaction between the Red oak, White oak, and maple species groups. The modeling of the Red oak group always resulted in an increase of importance value. This was an expected result, as the stands being observed were oak- dominated forests. The White oak group had some scenarios modeled at an increase but also had blocks that modeled a decrease or stagnation of Importance Value. This result was concerning as a comparison of the maple group to the Red oak and White oak groups. In all but one group, the Importance Value of maple started and ended higher than that of Red oak. When compared to the White oak group, the maple group had blocks where it matched or overtook the importance value of the White oak group; these dynamics were the result of the stagnation or decrease in the White oak groups. These results showed that the maple group typically had Importance Values that were greater than that of the Red oak group and Importance Values comparable or even competitive with the White oak group. This relationship indicates that the maple group typically started on par with the target oak groups and continued to maintain a similar status as the Red oak and White oak group. This result suggested that mesophication was already occurring throughout the blocks because the maple group was maintaining existing or increasing its prominence at rates comparable to the Red oak and White oak groups.

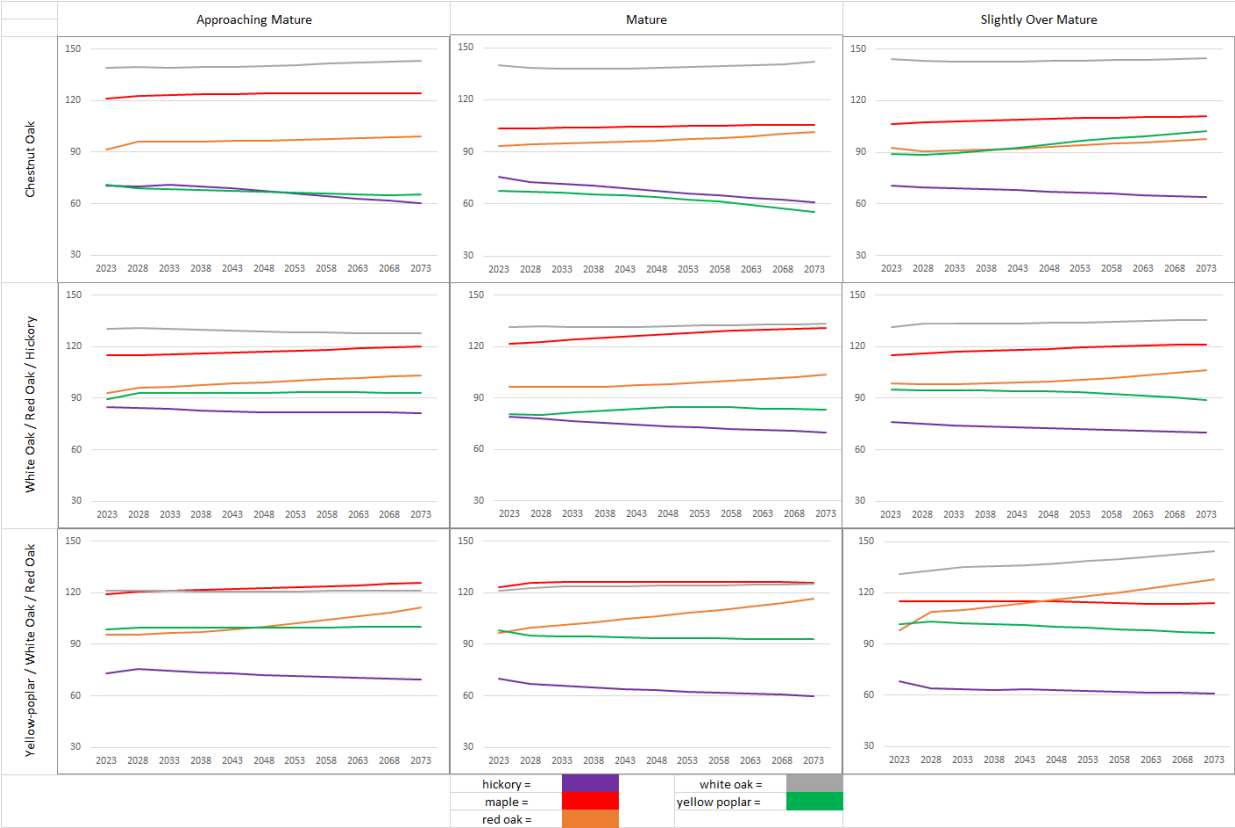


Figure 11: Average Change in Importance Value by Target Species Groups Sorted by Age Class and Forest Type

Likewise, these results suggest that the hypothetical carbon storage agreements would lend to the progression of this existing condition because of a lack of needed intervention. When modeled from the current states, the maple group continued to increase in importance value over the interval from an existing, significant representation in importance value at the beginning of the interval. This relationship was emphasized by the decrease of the hickory group. In a non-degraded scenario, the target hardwoods (Red oak, White oak, and hickory) would be expected to increase in importance and displace the prevalence of the maple group. This was not the case from these results, and they instead suggest the potential for further stand degradation in carbon storage agreements.

The Dominance portion of the Importance Value calculation was based on Basal Area, and basal area is a function of DBH. DBH maintained a positive relationship throughout the simulations (*Figure 12*). In the absence of mortality, trees continued to grow larger in these simulations. Comparing (*Figure 11*) to (*Figure 12*) showed that changes in Importance Value were not largely due to changes in Dominance or DBH. The maple group most consistently held the smallest average DBH (*Figure 12*). These observations meant that maple did not increase in Importance Value through Dominance, but through Frequency and Density. A large number of small, but vigorous and growing maples created these trends. The maples were frequent and dense, but not dominant. The other target hardwood groups were more dominant, but less frequent and less dense. These results showed that the prevalence of maple was modeled as a strength-in-numbers scenario and was comparable to the behavior of tree growth and reproduction where seedlings grow into larger trees through succession. The maple group should have a small-diameter growth component as it is a shade-tolerant species group growing and reproducing under canopy shade. However, in the expected proceedings of succession and in lieu of the existing effects of mesophication, the moderately shade-tolerant oak and Hickory groups should outcompete the shade-tolerant maple group and eventually suppressed this force. This relationship was missing in the other target species groups meaning that they did not exhibit the desired trends of small-diameter growth competition in these simulations.

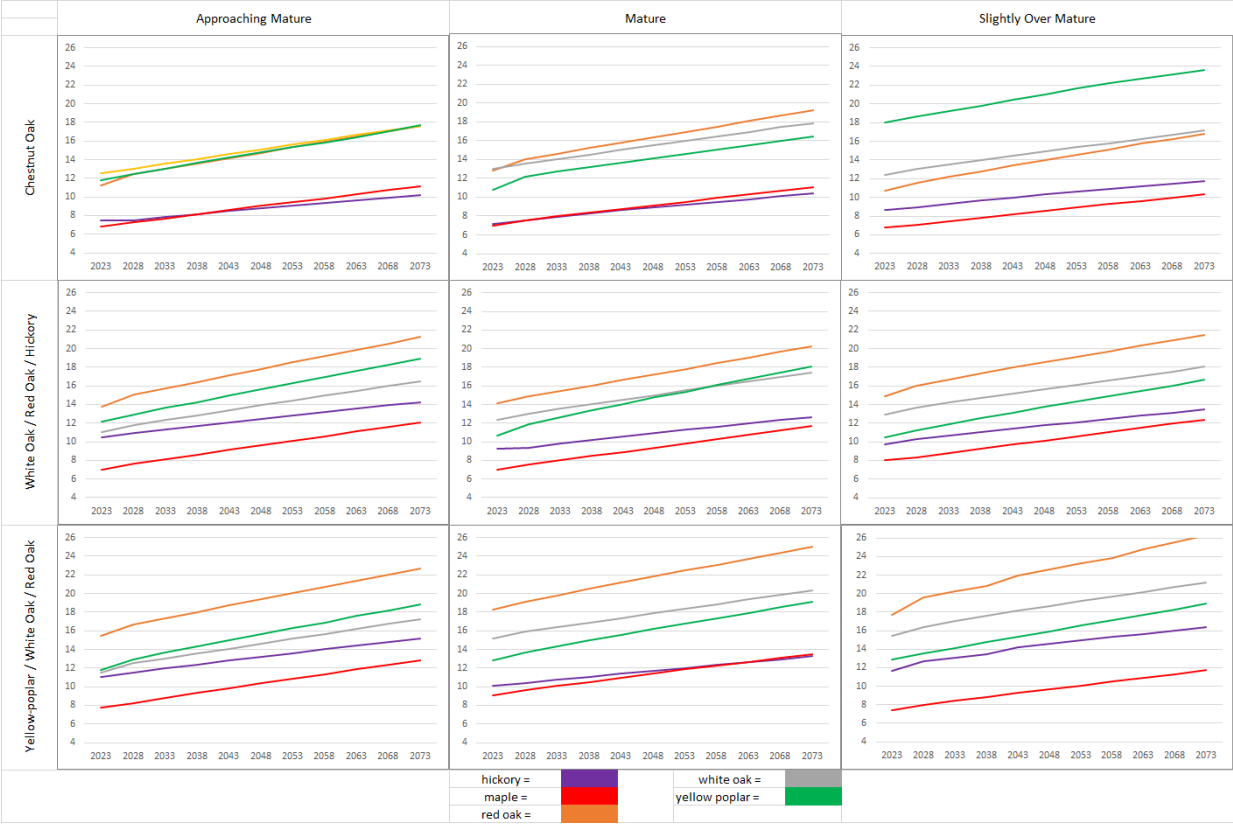


Figure 12: Average Change in DBH by Target Species Groups Sorted by Age Class and Forest Type

In these simulations, a strong force of small trees getting larger in the maple group without being hampered by other, larger diameter species groups was modeled; this relationship and the existing small diameter maple class is consistent with the indicators of mesophication. Oak and other hardwood small diameter growth in the needed competitive reproduction proportions was missing from the beginning of the simulations. This suggests the presence of existing mesophication in the forest plots and the modeled behavior of the simulations suggests a continuation of this degraded state. The class of small, persistent maples existing in the beginning and not being outcompeted by other species groups, was a modeled prediction of forest degradation and an ecological implication of carbon storage agreements in southern Appalachian hardwood forests.

These results showed indications of existing mesophication as well as modeled a furthering of forest degradation through mesophication. The maple group was shown to already hold significant prevalence and was modeled to continue increasing in prevalence against the more desirable oak groups; this same relationship was shown to displace and decrease the prevalence of the Hickory group. This is significant as it suggests that forests with existing degradation will degrade further under the precluded or reduced management regimes from carbon storage agreements. From an ecological perspective, the encouragement of mesophication is problematic for sustaining the species balance of southern Appalachian hardwood species. From a timber perspective, the modeled results of mesophication suggest that conditions for future growth of target species groups will be more difficult. In a maple dominated landscape, maple could continue being prevalent even after harvest disturbance. This prevalence could displace or hamper the ability of more desirable species groups (oaks and Hickories) to grow or reproduce. The time a forest spends in a reduced or precluded management carbon storage agreement retracts from the possible time spent making the same forest a cyclically producing, target species rich, timber environment. This means that landowners or stakeholders participating in carbon storage agreements could be contributing to ecological degradation as well as creating unfavorable timber growing conditions for their land in the future.

Products Output

Potential degradation effects were less apparent in product output. In (*Figure 13*), saw volume continued to increase while the pulp component remained largely unchanged. Larger trees continued to grow and added saw volume. Pulp trees continued to grow, graduated into saw trees, and added saw volume. Seedlings continued to grow and graduated into pulp trees; this graduation replaced the pulp volume lost by the graduation of pulp trees to saw trees. The results from (*Figure 12*) showed a similar trend to (*Figure 13*) where trees kept growing and gaining volume. Without sorting these product outputs into importance groups, the vertical growth trend appeared to support the hypothetical carbon agreements; board footage continued to increase, and pulp continued to transition.

In (*Figure 14*), a similar trend to (*Figure 13*) was shown. The board footage in most species groups continued to increase. Even though the maple group was consistently at the bottom for initial board footage, it outperformed or kept pace with the hickory group on several occasions for board foot growth. This result was consistent with the decrease in hickory importance value as shown in (*Figure 11*). However, comparing the two trends from (*Figure 13*) and (*Figure 14*) meant that more trees in the maple group were increasing their saw volume while also having pulp trees graduate to saw trees. Conversely, this meant that the hickory group was only having existing saw trees growing in volume. A similar relationship existed with the Yellow-poplar group however it was more expected; as a pioneer, shade-intolerant species group, Yellow-poplar was expected to decrease recruitment, gain volume only in existing trees, and ultimately decline in Importance Value. While the increasing board feet trend boded well for the hypothetical carbon agreements, this Importance Value tradeoff relationship was another suggestion of stand degradation.

Changes in species group volume over time were most apparent when the change in pulp volume was observed (*Figure 15*). There were only two ways for an increase in pulp volume to occur in these simulations: trees already in the pulp class could gain volume without getting too big to graduate into the saw class, or seedlings could gain volume and graduate into the pulp class. Both of these volume accumulation methods were time dependent (*Figure 15*).

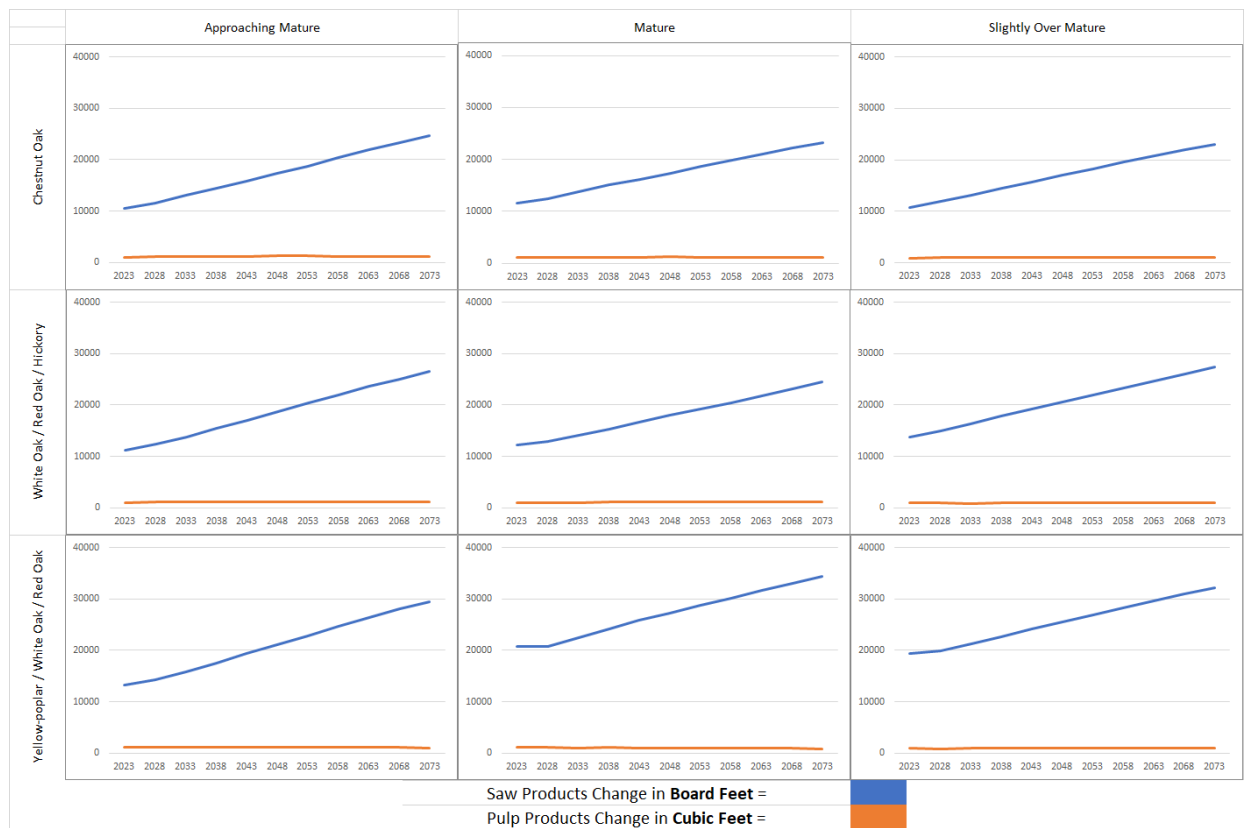


Figure 13: Average Change in Product Output Volumes Sorted by Age Class and Forest Type:
Pulp Volume in Cubic Feet, Saw Volume in Board Feet

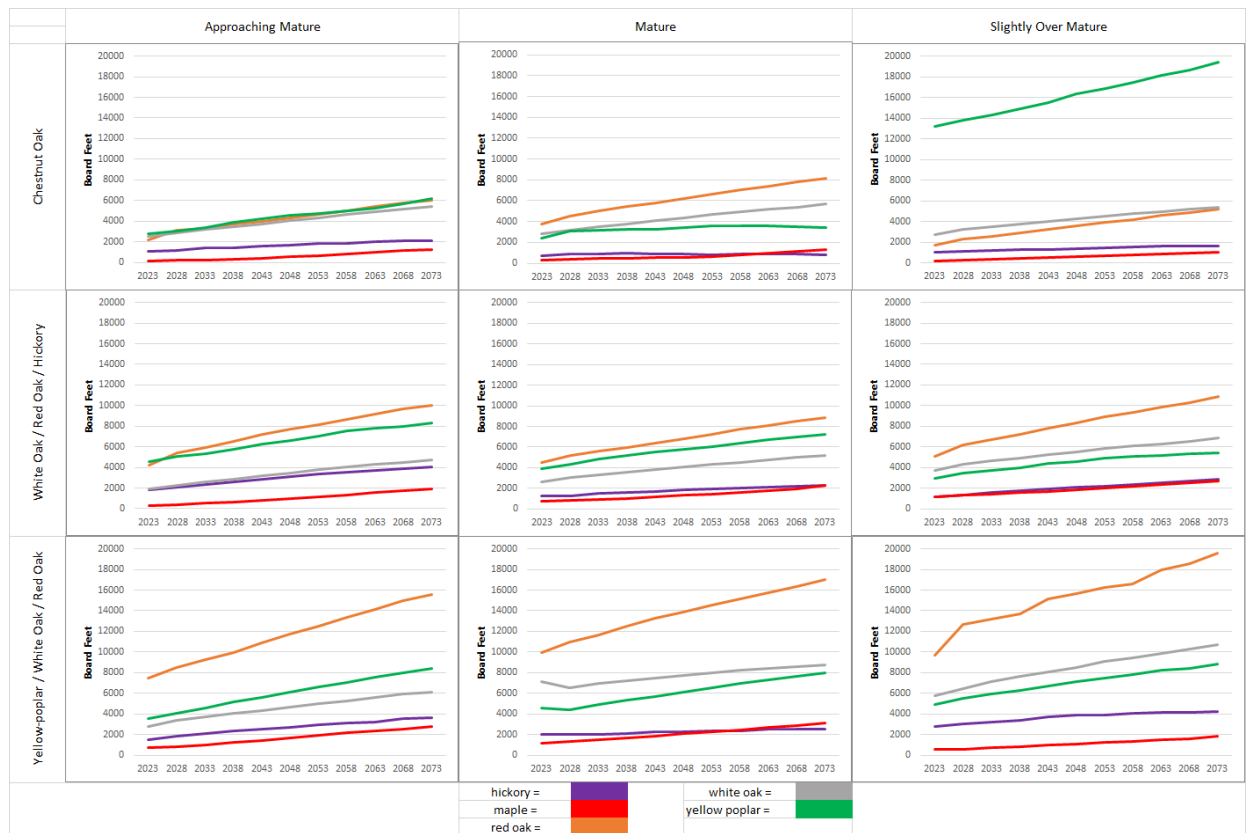


Figure 14: Average Change in Saw Product Output Volume in Board Feet by Target Species Groups Sorted by Age Class and Forest Type

Pulp volume in all target species groups was comparable at the beginning of the interval. As time progressed, the red oak, white oak, and hickory groups suffered an obvious decrease in pulp volume. This decrease was connected to the graduation of pulp trees to saw trees, without a corresponding increase in seedlings into pulp trees. The Yellow-poplar group also loosely followed this trend but had instances where an increase was shown; as a prolifically seeding species, these few increases in pulp volume could be due to existing heavy seedling presence. The maple class however showed a consistent increase in pulp volume. This meant that existing maple pulp trees continued to grow bigger and graduate into saw volume while also having a significant number of seedlings to pulp volume recruitments that were not observed in the other species grouping.

When compared to (*Figure 13*), (*Figure 15*) suggests that the stability of the pulp class was contingent on the increase found in the maple class; the maple group largely sustained the volume in the pulp classification. This trend was another suggestion of stand degradation where only the undesirable maple group had significant seedling presence to grow and fill the lower diameter classes. These trends were consistent with the concerns of mesophication where more shade-tolerant species were displacing the ability of desirable, moderately shade-tolerant, middle story hardwoods to reproduce. This was another indication of stand degradation and is also a concern for product class output where future forests will not have the species composition needed to make desirable products. Though board footage was modeled at an overall increase as shown in (*Figure 13*) and (*Figure 14*), the resulting forests were full of relatively undesirable maples. Based on these results, it was predicted that maple will ultimately dominate these stands, especially as the other desirable species succumb to mortality in future years. The maple group controlled the small diameter classes, was growing into larger saw classes, and displaced other, more desirable small-diameter growth in these simulations.

These results are significant as an increase in saw volume and a maintenance of pulp volume would initially bode well for the viability of carbon storage agreements. However, the concern with a change in product class is related to **future** potential of product outputs. The modeled recruitment of the maple group into pulp size trees paired with the decrease in recruitment of the oak and Hickory groups suggests undesirable future conditions for timber products output.

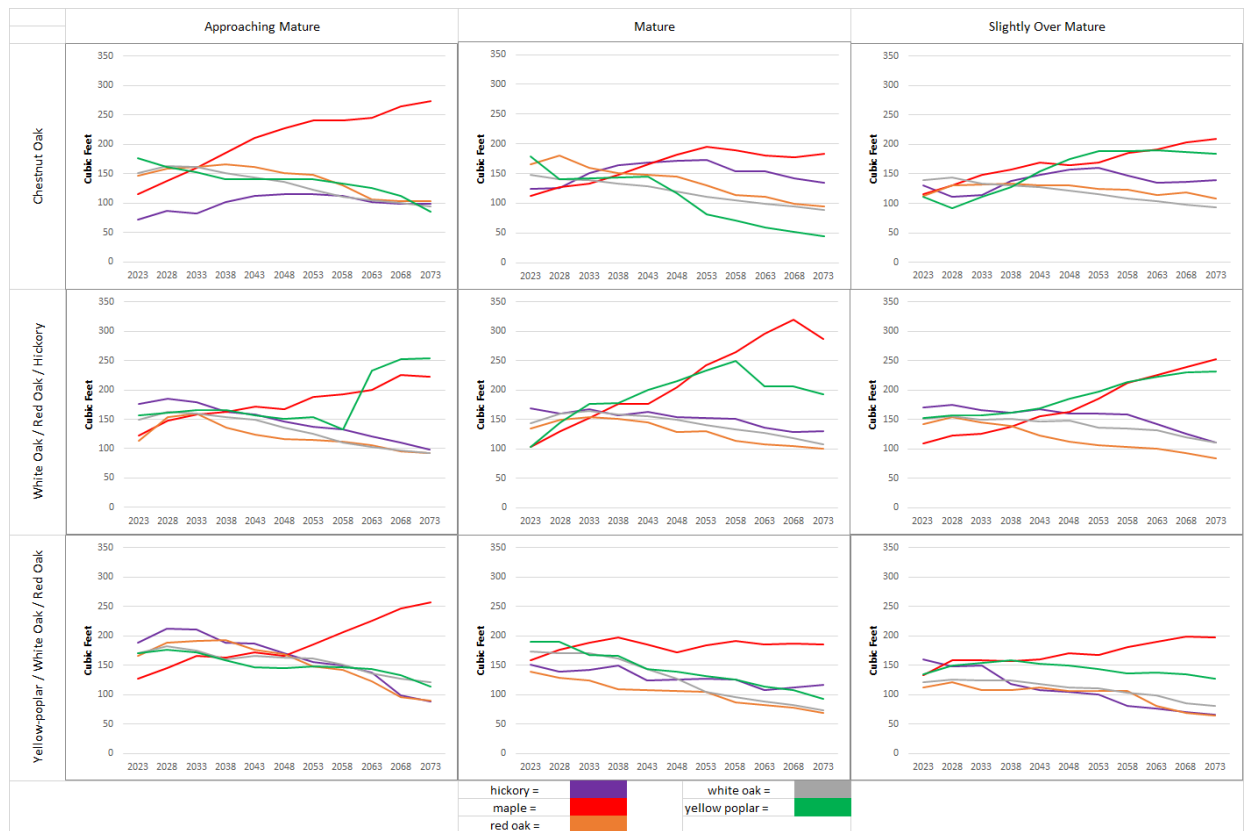


Figure 15: Average Change in Pulp Product Output Volume in Cubic Feet by Target Species Groups Sorted by Age Class and Forest Type

For the purposes of this thesis project, a change in product output is concerned with both the species of trees and their size; a desirable products output starts with a desirable species composition. In these simulations, the modeled increase of the maple group's volume is essentially a growth in products from the wrong species group. The degraded conditions depicted by an increase in the maple group mean that the future forest harvest post agreement interval will not be set up for the target species to grow and reproduce; instead, maple will be set up to grow and reproduce after harvest. For the southern Appalachian hardwood region, a product profile dominated by maples is undesirable (TimberMart-South, 2023). Similarly, a prolonging of the maple group in the absence of intentional management means that resources and growing space that could have been allocated to the desirable group was instead shared amongst all groups. While not quantified in this thesis project, it is possible that intentional suppression or removal of the undesirable maple group could have promoted the growth of the more desirable oak and Hickory groups. Much like the trends of mesophication detailed in the previous section, these results are significant to landowners and stakeholders because they suggest that future forests will not support desirable species growth. Likewise, the inability to control how and what species are growing within a forest could stifle potential desirable growth. This means that landowners or stakeholders participating in carbon storage agreements could be contributing to an undesirable shift in future timber products as well as losing significant growth potential to less valuable species groups.

Discussion on Creation of Results

The purpose of this discussion is to address the advantages and disadvantages of the methodology used in this project and how they might have affected the results produced. This project was a modeling endeavor, and as with any model, some concessions were made in the methodology. These concessions, or advantages, do not necessarily prove or invalidate the results produced. However, they are important considerations readers should be aware of and possible avenues for future research.

Sampling Population

For the creation of a sample population, only the most frequently occurring Forest Types in the predetermined Age Classes were used. While these simulations were able to make comments on a majority of the study area, they were not exhaustive. There were many forest plots that did not meet the predetermined criteria and were thus left out of this project. Similarly, this project was a randomized sample of the total plots that met the chosen criteria; a re-randomization could have potentially created different results. The data excluded from this project, specifically the less common Forest Types and forests of other Age Classes, could have yielded different results that do not follow the same trends of devaluing timber, species composition change, and altered products output. However, the sample population used was focused on the most commonly occurring Forest Types of the region and in Age Classes that would be most sensitive to the theoretical effects of carbon storage agreements. Likewise, these forests are what are most commonly connected to valuable timber harvesting in the region (TimberMart-South, 2023). While the results are not able to comment on every possible forest permutation in the region, they do comment on the most prominent forests that could likely end up in a carbon storage agreement and that would likely have a timber tradeoff dynamic. Additional studies addressing the less common Forest Types or other Age Classes would be needed to create a full suite of expected trends for carbon agreements in southern Appalachian hardwood forests.

Partial Establishment Model and Regeneration

The FVS Southern and FVS Northeast variants used in this thesis project operate on what is known as the “Partial Establishment Model” (FVS Staff, 2008). This is an FVS modeling parameter that covers the predictive abilities of seedling growth and regeneration in a forest plot (Dixon, 2002). In the “Partial Establishment Model,” users must input additional estimations for seedling regeneration behavior based on ground truth sampling. Otherwise, only the existing seedling regeneration initially recorded in the forest plot sampling will be modeled for the simulation duration. This project did not have access to additional seedling regeneration predictions and only used the default FVS settings applied to what regeneration was initially recorded in the FIA subplots. In the short, 50-year carbon storage interval, the most important dynamics to observe were the growth, mortality, and succession of existing trees and

regeneration. These are what were most impactful to the predicted trends in the results. However, holistically speaking the lack of continuous regeneration data is a missing piece of the forest model. The addition of this data could have added information or adjusted the predicted changes in species composition and products output. The maple group was predicted to grow in importance and ultimately dominate the simulated stand, but this prediction was in lieu of additional regeneration data from other groups. Based on the known trends of mesophication, this predicted transition to maple dominance would be expected. However, these trends of mesophication and unsuitability of future timber growth could have been modeled as less severe if a more detailed profile of tree regeneration was available. The predictive ability of the model addressed potential dynamic changes of existing growing stock but failed to fully account for all pieces of forest growth and succession. This means that even though the modeled trends observed were expected and in agreement with mesophication literature, they lack a portion of data needed for best possible predictions. This is significant as the simulation models are already only theoretical and not definitive ecological happenings. For better predictive abilities, an added framework of regeneration modeling would be needed. Such work has been explored Robinson (2007) in the article “Development of external regeneration models for FVS: Another wrench in the toolkit”

Plot Scaling Scheme

The most impactful caveat of this project was the way in which plots were scaled. The subplot units used were reported at 1/24-acre size and were then directly scaled up to one-acre parcels. While this scaling method followed traditional sampling characteristics where a 1/24-acre sample can appropriately represent one-acre of forest, it was not perfectly representative (Henning & Mercker, 2009). Under the traditional sampling characteristics, a typical forest sampling would have used multiple plots to create an average of a larger forest stand parcel; this project adapted those conventions to the single plot and 24X times scale. For the average, well-mixed, heterogeneous, and properly succeeding hardwood forest subplot, this scaling method likely did not render much of an effect. However, for individual subplots sampled with an obvious influence of a certain species, a high initial value, or a low initial value, a strong multiplier effect was observed. This effect would apply to subplots that had a high initial

sampling of something like valuable, mature White oak; a 1/24-acre plot with four valuable White oak trees became an acre of forest with 96 valuable white oak trees. Similarly, a 1/24-acre subplot full of only small pulp trees and regeneration became a full acre of nothing but small pulp trees and regeneration. The same could be true for mortality; a subplot with two valuable timber trees predicted to die early on in the simulations became an acre with 48 valuable timber trees predicted to die early. While not impossible, these compositions and behaviors were a result of scaling and would not typically occur naturally. Subplots with more heterogeneity common in southern Appalachian hardwood forests would not have been subject to the same severity of scaling skew. This scaling effect created instances in the results that would be considered ‘outliers’; the more homogenous subplots or subplots with unique species dynamics experienced would have been valued too high or low when scaled up to the acre size. While these instances were rare, some extremes were shown. The results produced were primarily concerned with general trends and these extremes would have been averaged out when observing the behavior of all plots as a whole. However, this is significant as confidence of this modeling methodology is dependent on the heterogeneity of the forest subplots used. Though the ‘outliers’ and subsequent scaling effects were few in this thesis project, further research could focus on how to best address homogeneous plot data or better scaling conventions.

Lack of Management or Disturbance Modeling

Due to the chosen data source, the simulations conducted in this project did not accommodate the inclusion of management or disturbance modeling. The scale used in this thesis project (1/24-acre subplots scaled to one-acre forest parcels) was too small to include these modeling parameters and usable forest trends were predicted without them. Many voluntary agreements allow some form of harvesting or management even if harvest allowance is only a fraction of the entire agreement parcel. These results mainly represent agreements that would have minimally allowed management regimes or agreements where management is neglected even if allowed. The same can be said for the likelihood of natural disturbance over a carbon storage agreement interval. Natural disturbance, even if comparably minor, would be very likely to occur to a forest over a 50-year interval. These results only represent optimistic growth scenarios where natural disturbance does not occur during the 50-interval. While the lack of these modeling parameters

does not invalidate these results, it does frame them in a narrower manner. Intentional management could have reduced the predicted timber degradation or species composition changes. Similarly, disturbance could have completely wiped out a forested plot creating a situation where even more value was lost. The scale at which this project was conducted is less than the scale at which these effects could be consistently applied. Although not included in this project, management and disturbance are frequent inclusions of similar modeling endeavors and are often their research focus. The exclusion of their use in this project means the results presented are best thought of as predictive forest behavior rather than commentary of the best way to apply carbon storage agreements in the region. Studies addressing how different management and disturbance regimes could affect carbon storage agreements in the southern Appalachian hardwood region, or a methodology for including them in a modeling project of this scale, would be good avenues of additional research.

FVS Prediction Inaccuracy

There are also limitations of the modeling capabilities of the FVS software. FVS has been shown in the past to inaccurately predict timber volume production in the southeastern US (Beasley, 2022). Similarly, FVS has been shown to over predict carbon volume estimations (Herbert, 2023). These limitations create a limbo where information about future forest conditions is needed, but current modeling capabilities do not always predict behavior with accuracy to real ecological occurrences. The results of this thesis project and trends suggested by them are contingent upon the accuracy of the modeling software used. If the estimations made by the modeling software for either timber, carbon, or both are incorrect, then the confidence of the calculated trends will suffer. The volume predictions used, though directly from the FVS software and based on real FIA forest data, might be dissimilar from the ground truth growing conditions of these forest subplots. This questionable estimation could have also been exaggerated by the scaling convention explained above. This kind of forest modeling research would benefit from ground truthing of the simulation results. This capability was not possible given the timeframe of the project and limitations on the use of FIA data. Efforts to better calibrate FVS for more accurate growth predictions have been made in works such as “Benchmarking and Calibration of Forest Vegetation Simulator Individual Tree Attribute Predictions Across the Northeastern United States” (Russell et al., 2013) Continued calibration

and ground testing could add confidence to the root FVS model and its derivations; this would be another avenue of continued research.

Climate Change Sensitivity

These simulations used in this thesis project were also not done with regards to climate change scenarios. At the time of this project, the climate-sensitive simulation input was only available in the Western variants of FVS, but not in the Southern or Northeastern variants used for this project (Crookston, 2014). This means that the predictive trends from this thesis project are not done with respect to increasing GHG accumulations in the atmosphere. Increasing CO₂ emissions and the resulting atmospheric temperature increase have been shown to have a fertilizing effect on plant growth (Dusenge et al., 2019). Given that CO₂ emissions are projected to continue increasing, this increase could encourage the growth of timber and storage of carbon (Hamdan et al., 2023). Therefore, because the simulations made in this project were done using current environmental conditions rather than predicted future conditions, the estimations of growing stock could be underestimated. This potential underestimation is another modeling concession that could have affected the confidence of the predicted trends. An article by Huiquan et al. explored the lack of climate predictions and explained how the lack of this metric might affect simulations in the Eastern Variants of FVS (Huiqua et al., 2015). Continued support and research on the effects of climate change on forest modeling is warranted.

Project Advantages

Despite the limitations described, this project had many advantages. The data used was real, expertly sampled, and geographically relevant forest plot data with enough information to predict timber and carbon stocking. The FIA data plots are high quality samplings and equivalent to if not more thorough than standard forest cruising plots. While this data format is overall different from what would typically be used to value a forest, the quality and applicability make the format transferable and defensible. Similarly, the modeling software used was the standard for forest behavior modeling and had existing metrics for the importation of the chosen data source. Despite the shortcomings of FVS, the software has proven capabilities and is consistently used in similar applications. The seamless and existing metrics for pairing FIA data to the FVS software

aided with this suitability. In addition to reputable data and modeling capabilities, the species groupings and prices used were regionally specific and determined by local experts and businesses. These regionally specific additions took the broad scope of plain FIA data and stock FVS modeling software into a narrowed analysis of southern Appalachian hardwood forests. Part of this narrowing was programming the project to include different sensitivities. Discount rate and carbon price were the two sensitivities used in this project, but the code was built in such a way that other sensitivities like timber prices, species groupings, and product classification cutoffs could be included with little adjustment. This sensitivity capability is valuable as the same simulations could be run with adjusted metrics to answer new research questions. Other researchers could adjust the included metrics or tweak the coding to incorporate new sensitivities; the code is built in sequential format such that careful addition of new sensitivities should not interfere with how the code runs as a whole. This sequential format starts with the input of plot data. Forest plot data from another region could easily be entered at the start and produce a similar analysis for entirely different regions. While the code is built to explore timber and carbon tradeoff dynamics for southern Appalachian hardwood forests, simple adjustments could easily change the dynamic focus and target forests.

While the modeling protocol from this thesis project could be adapted for similar regional analyses or adjusted sensitivities, the main advantage of this project was that the protocol could be adapted for site-specific forest parcel analyses. This project was created in a way such that the protocol and built code could be adapted for use on real forests rather than just composite forest plot data. The FVS software was usable for the modeling in the project, but it is more suited for true forest stand parcels. At the full forest parcel scale, these potential site-specific analyses could also include the modeling of management and disturbances. After the methodology of this project was built, the same process could be adapted to make predictions with expanded considerations on a real forested area. This advantage was congruent with the recommendations of expanding FIA and other federal ecological databases as described by Hover and Coeli (2020). If applied to real forest parcels, landowners, stakeholders, managers, and policymakers alike could use this methodology to determine the economic and environmental implications of entering into deferred harvest carbon storage agreements. This methodology could act as a decision-making tool for these interested parties to decide if a carbon storage agreement would

be profitable or if their participation would be contributing to some form of forest degradation. This is a capability largely missing from current available resources and should be a tool offered to protect both participants in carbon storage agreements as well as their forests.

Chapter 5: Conclusions

This project found the FIA to FVS methodology to be a viable way of predicting southern Appalachian hardwood forest behaviors under deferred harvest, carbon storage agreements. Using this methodology, results were created that made predictions on the economic and ecological implications of deferred harvest carbon credit agreements in the southern Appalachian hardwood region. These results suggest that carbon agreements in the region would potentially have negative consequences to southern Appalachian hardwood forests. Landowners and stakeholders could use these results to re-evaluate potential participation in carbon storage agreements while policymakers could use these results to influence the responsible implementation of carbon storage agreements in the region.

Discount Sensitivity and Time Value of Money

The southern Appalachian hardwood forests subplots modeled in this thesis project were projected to continue growing timber and sequestering carbon over the 50-year interval on average. However, even with this consistent growth, an overall loss in value was predicted when the modeled subplots were put into real world economic scenarios.

Even with consistent growth, the accumulation of timber and carbon volume was not enough to outpace inflation. A tradeoff was observed where the timber devalued too quickly, and accrued carbon value was not enough to recuperate the losses from timber. Against 3% inflation, over 60% of all simulated plots lost money. Even against the most basic economic force, the results suggest that carbon storage agreements in the southern Appalachian hardwood region will lose money a majority of the time.

This tradeoff and predicted loss were more severe when the plots were considered against an average 10% stock market investment scenario. At this rate, 98% of all plots were predicted to lose money by the end of the carbon agreement interval. These results suggest that harvesting timber and investing that revenue in a market return scenario would almost always be more profitable than entering a carbon storage agreement.

Southern Appalachian hardwood landowners considering entering a deferred harvest carbon credit agreement should be aware of the potential economic losses that could result from it. Participation should be chosen case by case and be based on transparent predictions of economic return.

Carbon Sensitivity

The economic tradeoff between timber and carbon was also sensitive to carbon price per ton. At all three prices modeled (\$10/ton the average voluntary price; \$50/ton the average social cost; and \$100/ton the average price reported by the EU) accrued carbon value was only predicted to offset the value lost from timber at the highest carbon price modeled.

Even at the EU carbon price, some loss was predicted on average. The tradeoff predicted at the end of the 50-year period was never a maximization of the potential value; the point of maximization was always surpassed earlier in the agreement interval at the EU carbon price. Some tradeoff was observed at the social cost of carbon as well, but most simulation blocks still usually lost money at the end of the interval and suffered the same lack of maximization.

These results suggest that the current voluntary carbon price is far too low for carbon agreements to be profitable in the southern Appalachian hardwood region. Even when the carbon price increased by a factor of 5X to meet the social cost of carbon or a factor 10X to meet the EU price of carbon, consistent loss in money was still predicted over the agreement interval. These results also suggest that common storage agreement interval lengths will push forests past their point of maximized value. Southern Appalachian hardwood landowners considering entering a deferred harvest carbon credit agreement should be aware that current voluntary carbon prices and agreement lengths are potentially unprofitable for the region.

Species Composition and Mesophication

Modeled changes in species composition were modest compared to the changes in value observed. The Red oak and White oak groups continued to increase in Importance Value, which suggested that the stands were not degrading. However, the maple group followed this same trend, at the consistent expense of the hickory group, and some expense of the Yellow-poplar group. While the maple class did not induce significant mortality or fully overtake species composition, it did have effects on one of the target hardwood groups and showed consistent, healthy growth along with the other target hardwood groups throughout all of the simulation blocks. The desirable hardwood groups were not able to outpace or suppress the encroaching maple class in this modeling meaning that mesophication was predicted to progress. These predictions were consistent with the definition of degradation by mesophication where the more shade-tolerant maple species group was able to grow in importance overtime where it otherwise should not (Radcliffe et al., 2021).

These results were produced at a stock growth assumption with no-harvest and non-disturbance scenarios. This means that while still historically influenced by anthropogenic changes, the only internal plot influence present was interspecies growth competition. Although this project had caveats in its modeling methodology, the results produced were predictions of how forests would behave in the reduced or precluded management environments of deferred harvest carbon credit agreements. Likewise, these predictions assumed that no other natural disturbances could affect tree growth; natural disturbance has the potential to reset all tree growth and make a plot completely lose value rather than just degrade. This suggests that the lack of management or intervention created by deferred harvest carbon storage agreements could be the cause of this predicted furthering of mesophication.

These results suggest that entering southern Appalachian hardwood forests into carbon storage agreements could encourage existing forest degradation from mesophication and that this encouragement would be from the lack of management related to these agreements. Landowners should be aware of these potential ecological consequences that could come with carbon storage

agreements in the region. Likewise, policymakers should be aware of this potential “co-benefit” involved with carbon storage agreements (Lee et al., 2018).

Wood Products Output

The trends of mesophication were supported by a change in product class volumes. The growth of the maple group’s pulp volume compared to the decline in pulp volume exhibited by the other species groups was an added indication of mesophication. Only the maple group showed a consistent increase in pulp volume in this modeling. This suggests that future stand dynamics beyond the 50-year agreement periods would likely be dictated by that strong, small-diameter, regenerating maple class in the absence of management intervention.

In the no-harvest model used here, board footage sawtimber volume was shown to increase, along with a steady maintenance stock of pulp volume. Though board footage volume in all the Importance Classes increased, this was less of a comment on stand degradation by mesophication and more of a comment on the setup of the simulation model. The lack of added mortality metrics, management, and modeled disturbances created a model that typically maintained the trees already in the forest stand plots; mortality was not excluded from this model, but the base metrics from FVS were potentially less severe than what would likely occur naturally (Crookston & Dixon, 2005).

Under typical forest management conditions, it could be recommended that the undesirable classes be suppressed to promote the more desirable species classes. Given that management was excluded in this model to emulate deferred harvest carbon storage agreements, the maple group mostly increased in Importance Value and in pulp volume overtime. Despite this increase in desirable board foot volume along with the undesirable pulp transition, this modeling predicted that the future forests would be dominated by the maple species group because of this transition. This predicted change in species composition and related volume transitions created modeled forests that were not conducive to the future regeneration or establishment of desirable saw product tree species such as oaks and Hickories. These results suggest that the undesirable maple group will be the dominant force after the theoretical agreement interval and waiting to take over

when existing trees of desirable groups (or board footage volume) are eventually removed or succumb to mortality.

The results of this project suggested that these future forests will not have the appropriate species composition to recreate existing, and desirable, forest species composition or products output. Landowners should be aware that carbon storage agreements could potentially limit the growth of existing, desirable timber; cause ecological degradation; and create forest conditions that are unable to support new desirable timber growth after eventual harvest. Likewise, policymakers should be aware that carbon storage agreements could potentially disrupt future supplies of desirable timber.

Relevance of Discussion to Stakeholders and Policymakers

Based on the results of this project, landowners and stakeholders should re-evaluate the viability of carbon storage agreements. These results suggest that these agreements are largely unprofitable against inflation or other investment opportunities and that current carbon prices are unable to make them profitable. This means that if carbon storage agreements are going to be a significant force in reducing climate change, policymakers might have to address financial incentives or subsidies to make them viable. These results also suggest that carbon storage agreements in the region could further existing ecological degradation that would affect future timber growth conditions and product supply. In the same fashion as potential subsidies, policy makers would have to work on restrictions that prevent the active encouragement of forest degradation for the viability of these agreements.

The predictions from this project call for continued research into carbon credit agreements in the southern Appalachian hardwood region. While this project tried to cover the important parts of forest modeling, there were many metrics that were unable to be included. Such modeling efforts that deserve further research include better representative regional sampling methods; climate change integration; small diameter growth and regeneration modeling; natural disturbance modeling; management modeling; and improved mortality metrics. Given all these moving parts and the highly diverse nature of the region, further research is needed to fully understand the

economic and ecological implications of carbon storage agreements in the region. The metric that this project suggests as most important is the need for active management under carbon storage agreements. The negative consequences predicted by this modeling were all made with a lack of modeled management. If agreements are going to be viable, it is likely that some form of management will be necessary.

The methodology and results in this project are a start at understanding the viability of carbon credit agreements in the southern Appalachian hardwood region; the work presented here should be expanded or adapted to further close the gap of understanding. In order to protect the economic interest of landowners and ecological interest of the forested areas, further research is needed to determine if carbon storage agreements in the southern Appalachian hardwood region are sustainably viable.

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Appendix

FIA National Forest Types Map

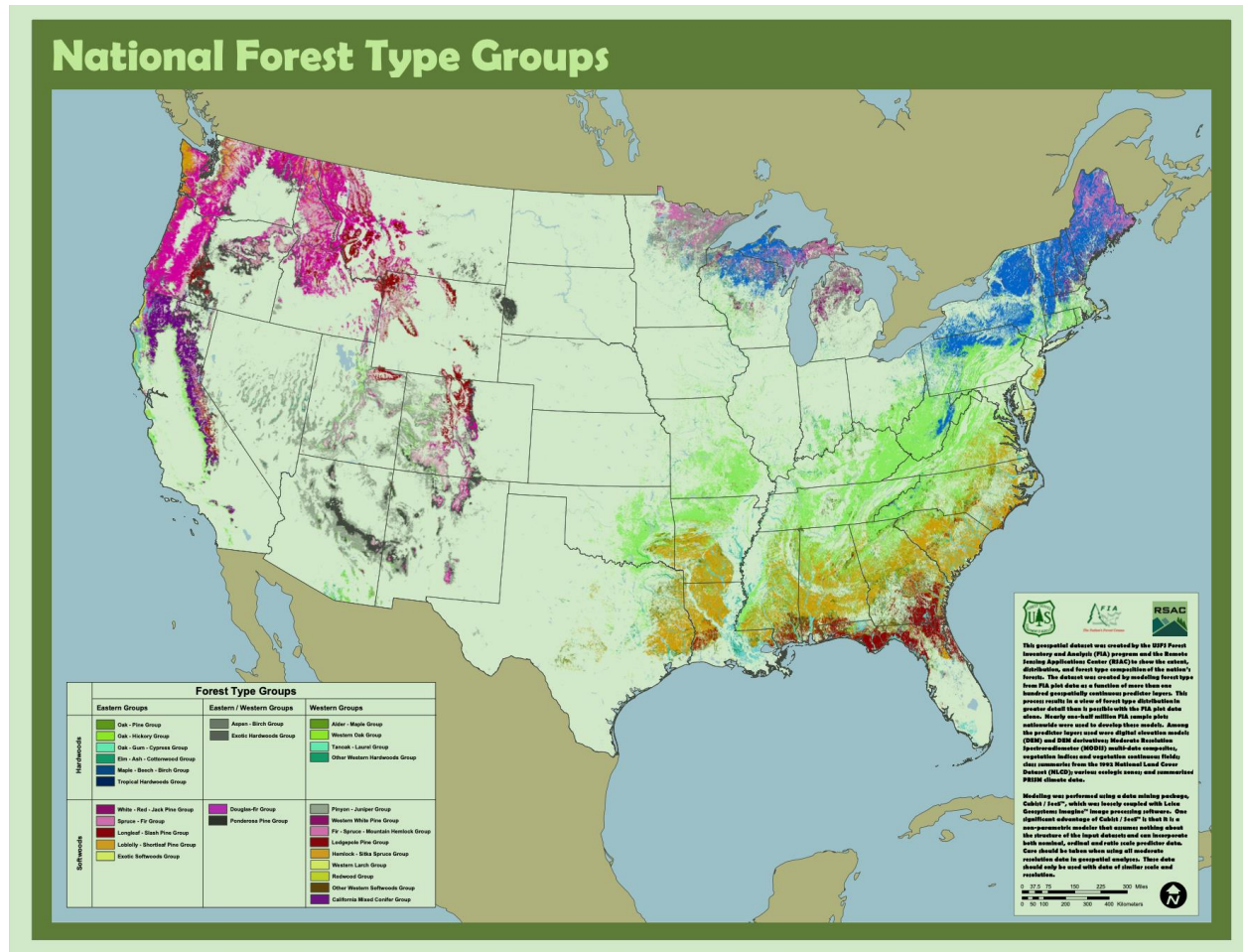


Figure 16: FIA National Forest Types Group Map (FIA, 2024)

FIA Species Codes Sorting by Timber Pricing Classes

Ash: 540, 541, 543, 544

Cherry: 762

Maple: 311, 313, 316, 317, 318, 315

Hickory: 400, 403, 409, 407

Red oak: 806, 812, 813, 819, 820, 824, 827, 833, 834, 837, 838, 800

White oak: 802, 822, 825, 826, 832, 835

Walnut: 601, 602

Sweetgum: 611

Yellow poplar: 621, 651

Pallet wood: 221, 222, 330, 370, 372, 391, 450, 460, 471, 491, 521, 531, 552, 555, 580, 591, 652, 653, 654, 660, 680, 691, 693, 694, 701, 711, 721, 731, 740, 743, 901, 920, 931, 950, 970, 971, 972, 975, 998, 999, 951, 500, 332, 356, 341, 371

**Pallet Wood was a grouping for all non-commercial hardwood trees that were greater than pulp sized*

Virginia pine: 10, 57, 90, 107, 110, 111, 115, 121, 123, 126, 128, 129, 131, 132, 260, 650, 057, 068, 261

**Virginia pine was a generalized grouping for all softwood trees that were saw sized*

Hardwood pulp: 540, 541, 543, 544, 762, 311, 313, 316, 317, 318, 400, 806, 812, 813, 819, 820, 824, 827, 833, 834, 837, 838, 802, 822, 825, 826, 832, 835, 601, 602, 611, 621, 651, 221, 222, 330, 370, 372, 391, 450, 460, 471, 491, 521, 531, 552, 555, 580, 591, 652, 653, 654, 660, 680, 691, 693, 694, 701, 711, 721, 731, 740, 743, 901, 920, 931, 950, 970, 971, 972, 975, 998, 999, 951, 500, 332, 356, 341, 371, 315, 403, 409, 407, 800

**Hardwood pulp was a grouping for all hardwood trees that were pulp sized*

Softwood pulp: 10, 57, 90, 107, 110, 111, 115, 121, 123, 126, 128, 129, 131, 132, 260, 650, 057, 068, 261

**Softwood pulp was a grouping for all softwood trees that were pulp sized*

Full Suite of R Code Used for Post-Processing of FVS Simulation Results

```
---
title: "THESIS CODE REVISED"
author: "Database"
date: "2023-11-17"
output: html_document
---

```{r}
library(tidyverse)
library(readxl)
library(janitor)
library(dplyr)
library(ggplot2)
```

```{r}
stand_data <- read_csv("C:/Users/jareth/onedrive/Desktop/Thesis Excel
Sheets/NewNewFinalAllTrees.csv") %>% clean_names()
```

```{r}
species_table <- read_xlsx("C:/Users/jareth/OneDrive/Desktop/Thesis Excel
Sheets/SpeciesAndPriceTable.xlsx" , sheet = 1, range = "A1:M85") %>% clean_names()

(species_table)
```

```{r}
stand_data <- stand_data %>%
 mutate(product_class = case_when(
 species_fia %in% species_table$ash & dbh >= 12 ~ "ash",
 species_fia %in% species_table$cherry & dbh >= 12 ~ "cherry",
 species_fia %in% species_table$maple & dbh >= 12 ~ "maple",
 species_fia %in% species_table$hickory & dbh >= 12 ~ "hickory",
 species_fia %in% species_table$red_oak & dbh >= 12 ~ "red_oak",
 species_fia %in% species_table$white_oak & dbh >= 12 ~ "white_oak",
 species_fia %in% species_table$walnut & dbh >= 12 ~ "walnut",
 species_fia %in% species_table$sweetgum & dbh >= 12 ~ "sweetgum",
 species_fia %in% species_table$yellow_poplar & dbh >= 12 ~ "yellow_poplar",
```

```

species_fia %in% species_table$palletwood & dbh >= 12 ~ "palletwood",
species_fia %in% species_table$virginia_pine & dbh >= 10 ~ "virginia_pine",
species_fia %in% species_table$hardwood_pulp & dbh < 12 & dbh >= 6 ~ "hardwood_pulp",
species_fia %in% species_table$softwood_pulp & dbh < 10 & dbh >= 4 ~ "softwood_pulp",
TRUE ~ "seedling"
), top_pulp_price = case_when(species_fia %in% species_table$hardwood_pulp ~ 0.18, TRUE
~ 0.13))
```


```

```{r}
price_table <-
  read_xlsx(
    "C:/Users/jareth/OneDrive/Desktop/Thesis Excel Sheets/SpeciesAndPriceTable.xlsx" , sheet
= 2, range = "A1:D15"
  ) %>% clean_names %>% rename(product_class = x1)

(price_table)
```


```

```{r}
price_table_long <- price_table %>%
 mutate(product_class = make_clean_names(product_class)) %>%
 gather(-product_class, key = "category", value = "price")
```


```

```{r}
stand_data <- stand_data %>%
  mutate(category = case_when(between(dbh, 3, 16) ~ "lo",
                              between(dbh, 16, 24) ~ "med",
                              dbh > 24 ~ "hi",
                              TRUE ~ NA))
```


```

```{r}
stand_data <- stand_data %>%
 left_join(price_table_long)
```


```

```{r}
stand_data <- stand_data %>%
  mutate(price = case_when(product_class == "seedling" ~ 0,
                           TRUE ~ price))
```


```

```{r}

```


```


```


```


```


```


```



```

stand_data_summary<-stand_data_summary %>%
 left_join(carbon_data)

stand_data_summary<-stand_data_summary %>%
 group_by(stand_id) %>%
 mutate(initial_stand_carbon = case_when(year == '2023' ~ total_stand_carbon)) %>%

fill(initial_stand_carbon)

stand_data_summary<-stand_data_summary %>%
 group_by(stand_id) %>%
 mutate(total_carbon_increment = total_stand_carbon - initial_stand_carbon)

stand_data_summary<-stand_data_summary %>%
 mutate(carbon_ton_value = 10)

stand_data_summary<-stand_data_summary %>%
 mutate(carbon_ton_value_social = 50)

stand_data_summary<-stand_data_summary %>%
 mutate(carbon_ton_value_EU = 100)

stand_data_summary<-stand_data_summary %>%
 mutate(total_carbon_value = total_carbon_increment*carbon_ton_value*3.67)

stand_data_summary<-stand_data_summary %>%
 mutate(total_carbon_value_social = total_carbon_increment*carbon_ton_value_social*3.67)

stand_data_summary<-stand_data_summary %>%
 mutate(total_carbon_value_EU = total_carbon_increment*carbon_ton_value_EU*3.67)

...
```{r}
stand_data_summary <- stand_data_summary %>%
  mutate(
    final_value = ((timber_value_sum + total_carbon_value) / (1 +
      0.03
    ) ^ (
      as.numeric(year) -
      2023

```

```

)) %>%

group_by(stand_id) %>%
mutate(
  initial_value = case_when(year == min(year) ~ final_value,
                             TRUE ~ NA)) %>%

fill(initial_value) %>%
mutate(delta_final_value = (final_value - initial_value)
) %>%

filter(between(year, 2023, 2073),!is.na(age_class))
```
Relative
```{r}
stand_data_summary <- stand_data_summary %>%
mutate(age_class = str_remove(age_class, "\""),
       age_class = str_remove(age_class, "\\\""),
       age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
```
```{r}
stand_data_summary <- stand_data_summary %>%
mutate(
  final_value_social = ((timber_value_sum + total_carbon_value_social) / (1 +
    0.03
  ) ^ (
    as.numeric(year) -
    2023
  )),
  year = as.numeric(year)) %>%

group_by(stand_id) %>%
mutate(
  initial_value_social = case_when(year == min(year) ~ final_value_social,
                                   TRUE ~ NA)) %>%

fill(initial_value_social) %>%
mutate(delta_final_value_social = (final_value_social - initial_value_social)%>%

filter(between(year, 2023, 2073),!is.na(age_class))

```

```

...
```{r}
stand_data_summary <- stand_data_summary %>%
 mutate(age_class = str_remove(age_class, "\""),
 age_class = str_remove(age_class, "\""),
 age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
...
```{r}
stand_data_summary <- stand_data_summary %>%
  mutate(
    final_value_EU = ((timber_value_sum + total_carbon_value_EU) / (1 +
      0.03
    ) ^ (
      as.numeric(year) -
      2023
    )), year = as.numeric(year)) %>%

  group_by(stand_id) %>%
  mutate(
    initial_value_EU = case_when(year == min(year) ~ final_value_EU,
                                TRUE ~ NA)) %>%

  fill(initial_value_EU) %>%
  mutate(delta_final_value_EU = (final_value_EU - initial_value_EU)) %>%
  filter(between(year, 2023, 2073), !is.na(age_class))
...
```{r}
stand_data_summary <- stand_data_summary %>%
 mutate(age_class = str_remove(age_class, "\""),
 age_class = str_remove(age_class, "\""),
 age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
...
```{r}
stand_data_summary <- stand_data_summary %>%
  mutate(
    final_value_stock = ((timber_value_sum + total_carbon_value) / (1 +
      0.1
    ) ^ (
      as.numeric(year) -
      2023

```

```

)),year = as.numeric(year)) %>%

group_by(stand_id) %>%
mutate(
  initial_value_stock = case_when(year == min(year) ~ final_value_stock,
    TRUE ~ NA)) %>%

fill(initial_value_stock) %>%
mutate(delta_final_value_stock = (final_value_stock - initial_value_stock)) %>%

filter(between(year, 2023, 2073),!is.na(age_class))

stand_data_summary <- stand_data_summary %>%
mutate(age_class = str_remove(age_class, "\\\""),
  age_class = str_remove(age_class, "\\\""),
  age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
...
```{r}
stand_data_summary <- stand_data_summary %>%
mutate(
 raw_value = ((timber_value_sum + total_carbon_value)),
 year = as.numeric(year)) %>%

group_by(stand_id) %>%
mutate(
 raw_initial_value = case_when(year == min(year) ~ raw_value,
 TRUE ~ NA) %>%
fill(raw_initial_value) %>%
mutate(delta_raw_value = (raw_value - raw_initial_value)) %>%

filter(between(year, 2023, 2073),!is.na(age_class))

...
```{r}
stand_data_summary <- stand_data_summary %>%
mutate(age_class = str_remove(age_class, "\\\""),
  age_class = str_remove(age_class, "\\\""),
  age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
...

```

```

```{r}
stand_data_summary <- stand_data_summary %>%
 mutate(total_carbon_value_discounted = ((total_carbon_value) / (1 +
 0.03
) ^ (
 as.numeric(year) -
 2023)))

stand_data_summary <- stand_data_summary %>%
 mutate(total_carbon_value_discounted_social = ((total_carbon_value_social) / (1 +
 0.03
) ^ (
 as.numeric(year) -
 2023)))

stand_data_summary <- stand_data_summary %>%
 mutate(total_carbon_value_discounted_EU = ((total_carbon_value_EU) / (1 +
 0.03
) ^ (
 as.numeric(year) -
 2023)))

stand_data_summary <- stand_data_summary %>%
 mutate(timber_value_discounted = ((timber_value_sum) / (1 +
 0.03
) ^ (
 as.numeric(year) -
 2023)))%>%

group_by(stand_id) %>%
mutate(
 timber_initial_value_discounted = case_when(year == min(year) ~ timber_value_discounted,
TRUE ~ NA)) %>%

fill(timber_initial_value_discounted) %>%
mutate(
 delta_timber_value_discounted = (timber_value_discounted -
timber_initial_value_discounted)) %>%

filter(between(year, 2023, 2073),!is.na(age_class))

```

```

stand_data_summary <- stand_data_summary %>%
 mutate(age_class = str_remove(age_class, "\\\""),
 age_class = str_remove(age_class, "\\\""),
 age_class = factor(age_class, levels = c("60-80", "81-100", "101-120")))
...
```{r}
stand_data <- stand_data %>%
  mutate(product_class_importance = case_when(
    species_fia %in% species_table$ash ~ "ash",
    species_fia %in% species_table$cherry ~ "cherry",
    species_fia %in% species_table$maple ~ "maple",
    species_fia %in% species_table$hickory ~ "hickory",
    species_fia %in% species_table$red_oak ~ "red_oak",
    species_fia %in% species_table$white_oak ~ "white_oak",
    species_fia %in% species_table$walnut ~ "walnut",
    species_fia %in% species_table$sweetgum ~ "sweetgum",
    species_fia %in% species_table$yellow_poplar ~ "yellow_poplar",
    species_fia %in% species_table$palletwood ~ "palletwood",
    species_fia %in% species_table$virginia_pine ~ "virginia_pine",
    TRUE ~ "Unknown"
  ))
...
```{r}
stand_data_abundance_dominance <- stand_data %>%

 group_by(stand_id, year, forest_type, age_class) %>%

 mutate(

 ba_tree = 0.005454 * dbh^2,
 ba_tpa = ba_tree * tpa) %>%

 mutate(ba_sum = sum(ba_tpa),
 tpa_sum = sum(tpa)) %>%
group_by(stand_id, year, product_class_importance, ba_sum, tpa_sum, forest_type, age_class)
%>%

summarise(tpa_product_class = sum(tpa),

```

```

 ba_product_class = sum(ba_tpa)) %>%

mutate(relative_abundance = tpa_product_class / tpa_sum * 100,

 relative_dominance = ba_product_class / ba_sum * 100)

stand_data_frequency <- stand_data_abundance_dominance %>%

group_by(forest_type,age_class) %>%

mutate(n_plots = length(unique(stand_id))) %>%

group_by(year, forest_type,age_class, n_plots) %>%

#group_by(stand_id, species, n_plots) %>%

count(product_class_importance) %>%

mutate(relative_frequency = n / n_plots *100) %>%

ungroup()

stand_data_IV <- stand_data_abundance_dominance %>%

group_by(year, product_class_importance, forest_type, age_class) %>%

summarise(mean_relative_abundance = mean(relative_abundance),

 mean_relative_dominance = mean(relative_dominance)) %>%

left_join(stand_data_frequency %>% select(year, product_class_importance,
relative_frequency)) %>%

mutate(IV = mean_relative_abundance + mean_relative_dominance + relative_frequency)
```


```

```{r}
stand_data_average_product_class_dbh <- stand_data %>%
group_by(stand_id, year,forest_type,age_class,product_class_importance) %>%

```


```

```

summarise(average_dbh = mean(dbh),
 average_board = mean(board_amounts),
 average_pulp = mean(pulp_amount),
 average_mortality = mean(mort_pa))%>%

group_by(year, age_class, forest_type, product_class_importance) %>%
summarise(average_dbh = mean(average_dbh),
 average_board = mean(average_board),
 average_pulp = mean(average_pulp),
 average_mortality = mean(average_mortality))

```

## Vita

Originally from Tennessee, Jareth Beeler grew up in Knoxville, Tennessee. After high school, he attended the University of Tennessee, Knoxville and received a Bachelor of Science degree in Forestry, Resource Management. Before graduating with his undergraduate degree, he knew he wanted to attend graduate school. He chose to remain at the University of Tennessee, Knoxville to pursue a Master of Science degree in Forestry with a concentration in Carbon Sequestration. His research interest includes studying the economic tradeoff of managing Southeastern, Appalachian forests for both timber and carbon. After graduation, he hopes to begin working a position in the forest carbon sector. He is incredibly grateful for all the support from his partner, family, and friends as he begins his new career.